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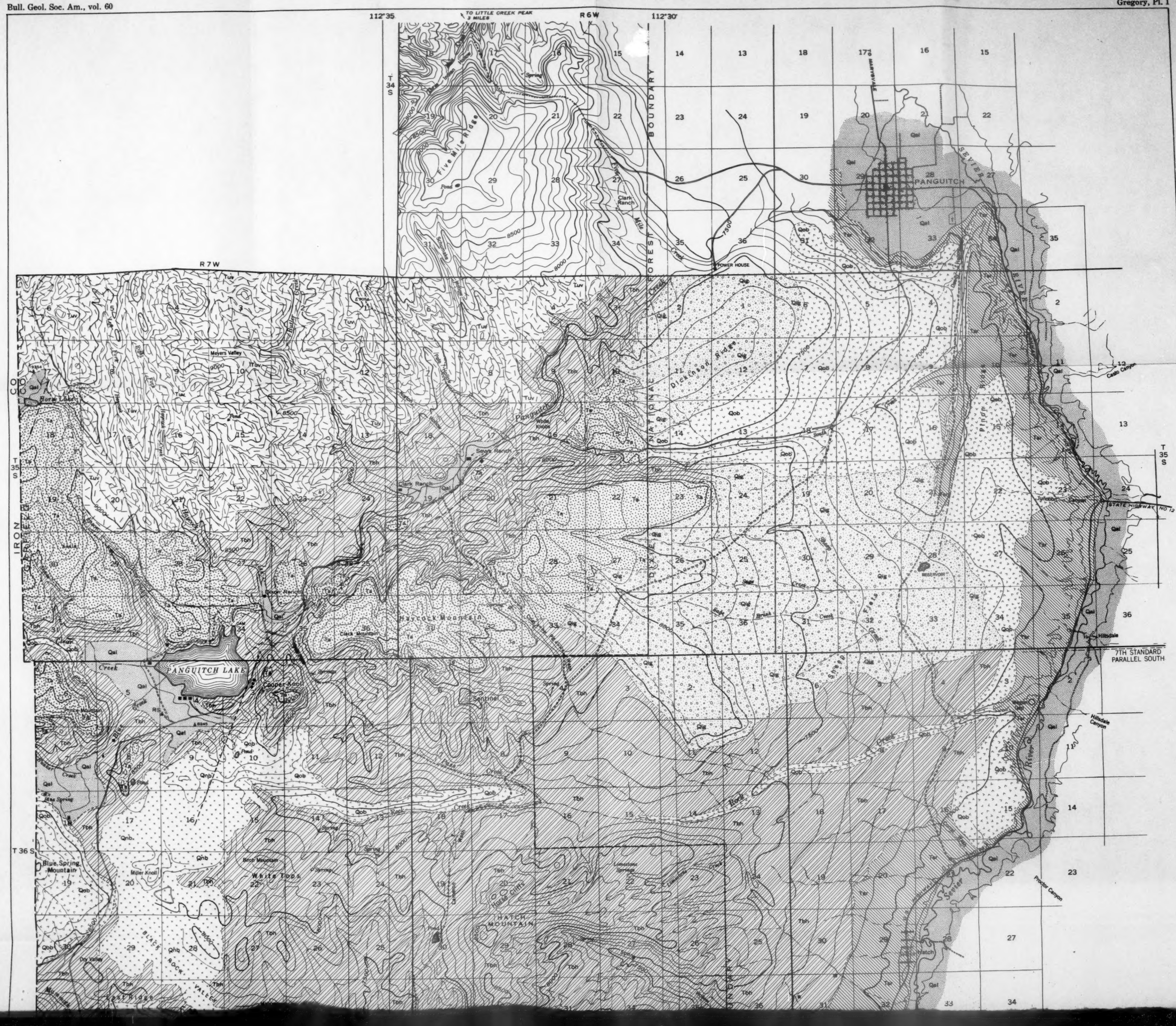
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POWER HOUSE
PANGUITCH
SEVIER
R7W
Meyers Valley
Horse Lake
Panguitch
White Knobs
Sevey Ranch
Haycock Mountain
Clark Mountain
Dicks Head Ridge
Pine Ridge
Cedar Canyon
Tunnel Canyon
Hillsdale
Hillsdale Canyon
Proctor Canyon
STATE HIGHWAY NO 12
7TH STANDARD PARALLEL SOUTH
IRON
GARFIELD
PANGUITCH LAKE
Cooper Knoll
Sentinel
Blue Spring Mountain
Miller Knoll
White Tops
Birch Mountain
HATCH MOUNTAIN
Horse Cliffs
Limestone Springs
Black Rock Valley
East Ridge
T 35 S
T 36 S

MAP OF THE EASTERN MARKAGUNT PLATEAU, UTAH

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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GEOLOGIC AND GEOGRAPHIC RECONNAISSANCE OF EASTERN MARKAGUNT PLATEAU, UTAH

BY HERBERT E. GREGORY

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ABSTRACT

The eastern Markagunt Plateau is a characteristic part of the extensive Markagunt Plateau—an uplifted, eastward-tilted earth block that lies between the Hurricane and Sevier faults in Garfield and Kane counties, Utah. The exposed sedimentary rocks are Tertiary—representatives of the Wasatch, Brian Head, and Sevier River formations. Rocks of volcanic origin include lavas and pyroclastics. The oldest extrusive rocks are porphyritic andesites, of doubtful origin. Next in order are the "old basalts," which during two or more periods flowed from widely spaced craters over flat lands and far down stream channels, and in the present topography cap mesas, ridges, and the palisade walls of canyons. Very recent volcanic activity is recorded by little-modified cones, long narrow flows, broad sheets, and fields of olivine basalt.

The plateau (average altitude, 8,000 feet), uninhabited because of its inhospitable climate, is part of the Dixie National Forest—a summer grazing district and a source of marketable timber. The snow that covers the plateau for 6–8 months each year feeds the streams utilized for irrigation at Panguitch, Hillsdale, and Hatch.

INTRODUCTION

PURPOSE AND SCOPE OF INVESTIGATION

Geologic reports prepared in recent years deal with the Paunsaugunt and the western Markagunt Plateaus but omit consideration of the intervening eastern Markagunt. This paper is designed to complete the geographic and geologic reconnaissance of the highlands that lie between the upper Paria River Valley and the eastern margin of the Great Basin—between the Paunsaugunt and the Hurricane faults. The field work in 1943, 1944, and 1945 involved the compilation of a base map, the description of the sedimentary rocks, and the segregation of the various types of lavas and pyroclastics. Recording the geographic features was aided by the regional maps prepared by Dutton (1872) and the Forest Service (1916), and the map of a narrow strip along the South Fork of the Sevier River published by the Geological Survey (Woolley, 1947). The scales and contour intervals of these maps vary widely, the adopted datum planes differ as much as 290 feet, and superposition reveals inconsistencies of position and altitude too great to be reconciled except by surveys beyond the scope of reconnaissance studies. Therefore, in preparing the present report these maps were used in combination after adjustment of their borders and the re-location of contour lines where instrumental measurements showed marked discrepancies. The resulting map, though unsuitable for showing the picturesque land forms developed by erosion, permits the recording of geologic features with reasonable approximation. Fortunately the various types of rock cover areas of considerable size and in mass are easily distinguishable.

PREVIOUS GEOLOGIC WORK

The eastern Markagunt Plateau is included in the area examined by the Wheeler and the Powell surveys. Wheeler (1875) outlined the drainage system for the first

time and noted the source of some of the lava flows. Gilbert (1875) briefly described the sedimentary rocks, including a measured section in Asay Creek Valley. Dutton (1879) gave attention to the composition of the lavas and pyroclastics of the Panguitch Lake region and roughly mapped the area which, in his opinion, constituted a volcanic field. These pioneer scientists treated the geologic features of the eastern Markagunt as the relatively unimportant duplicates of those more carefully studied on the western Markagunt and the Sevier and Tushar Plateaus.

GEOGRAPHY

LOCATION AND ACCESSIBILITY

The eastern Markagunt Plateau lies in southwestern Garfield and northwestern Kane County, Utah (Fig. 1; Pl. 1), between parallels 37°35′ and 37°50′, and meridians 112°25′ and 112°42′. Its south boundary is the crest of the Pink Cliff; its east boundary the South Fork of the Sevier River; its north boundary, the town site of Panguitch, and its west boundary the division line between Garfield and Iron Counties. The area, about 390 square miles, is an expanse of high-lying grazing and timber land—most of it within the Dixie National Forest—bordered on the east and northeast by strips of agricultural land suitable for irrigation. The population is grouped at the base of the plateau in the villages of Panguitch and Hatch through which passes Federal highway 89, the only road in the region that is kept in repair and open to traffic throughout the year. From Panguitch, Hatch, and Gravel Junction, unpaved, partly graded roads extend to Cedar City, Cedar Breaks, and Parowan, and connect Panguitch Lake with Duck Creek Sinks. Many short, crooked roads and broad trails used by stockmen and lumbermen cross the relatively flat highlands and follow dry valleys or the edge of lava flows. During the long winter season, all roads and trails on the plateau are deeply buried in snow.

CLIMATE

The climate of the eastern Markagunt Plateau is characterized by long cold winters with abundant snow fall; short, moderately warm summers with brilliant sunshine and infrequent rains—usually heavy and short lived; and delightfully cool springs and autumns, when light, erratically timed showers occur. The climatic conditions on the plateau top may be roughly approximated by reference to those along the margin of the plateau at Panguitch (altitude 6,700 feet) and Hatch (altitude 7,000 feet) where stations of the United States Weather Bureau are in operation.

At Panguitch, which ranks with Widtsoe and Laketown as the coldest meteorological stations in Utah, recorded average temperatures are: spring, 40.1°F; summer, 60.6°F; fall, 40.3°F; and winter 23.1°F. For 5 months in the year temperatures below zero have been recorded— the lowest 38° below; even in summer, temperatures above 90° are rare. Ordinary years have killing frosts as late as June 20 and as early as September 8, and in exceptional years even during July and August. The average interval between frosts is thus but 80 days—the minimum 41 days and the maximum 128 days—probably the shortest growing season to which agricultural practise in Utah has been adjusted.

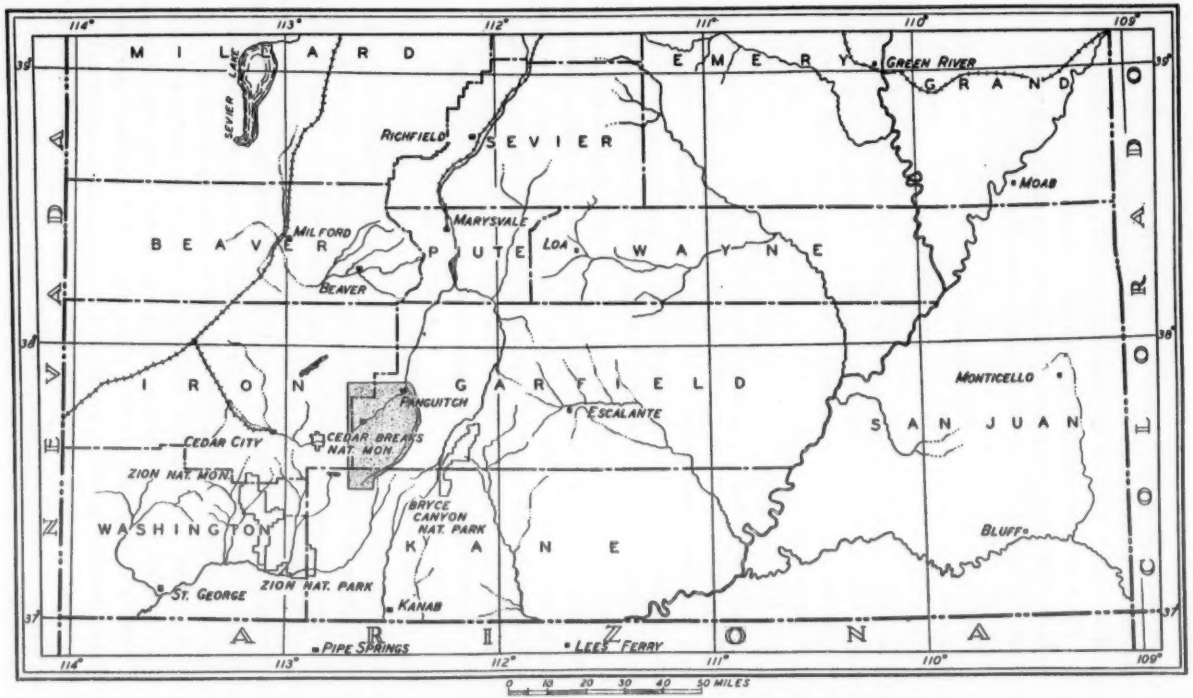

FIGURE 1.—*Outline map of southern Utah showing the location of the eastern Markagunt Plateau*

The recorded mean annual rainfall at Panguitch is 9.68 inches; maximum, 18.2 inches (1910), minimum, 5.44 inches. For Hatch, the corresponding figures are 11.28, 15.74, and 6.80. Before reaching villages in the Sevier River Valley, the prevailing regional winds leave much of their moisture along the western rim of the Markagunt Plateau. As if in compensation for the widely spaced and relatively light rains, snowfalls are frequent and heavy. Above the 8,000-foot contour line, snow may fall every month, and usually for 7 or 8 months it forms a continuous mantle and in places stands as drifts as much as 30 feet high. Even at Panguitch, snow storms are recorded for all months except July and August. Measurements made by the National Park Service in March, when the snow is most compact, show a mean annual accumulation of 19.4 inches at Panguitch Lake; 23.45 inches at Gravel Pass; 30.42 inches at Harris Flat; 33.1 inches at Panguitch; 41.00 inches at Duck Creek; and 70+ inches in the highest valleys. Furthermore, the water content of the snow is exceptionally large. The estimated average annual precipitation is 30 inches for the Markagunt Plateau—for parts of it perhaps as much as 35 inches.

Snow is the controlling factor in determining the habitability, the mode of life, and the economic development of the region that includes the eastern Markagunt Plateau. During the short growing season the normal run-off from rainfall is meager, erratically fluctuating in time and amount, and therefore difficult to utilize. Much of it goes into the ground through innumerable sink holes and, emerging as springs, feeds the irrigation ditches during the months when it is imperatively needed. Because of the heavy snows, the usual grazing season for cattle on the Markagunt is July 1 to September 15, and for sheep, June 1 to September 30. After the first heavy autumn snow the plateau is completely vacated, no attempts are made to maintain roads or trails, and patrolling rangers travel on skis. During the long winter, outlying ranch homes are abandoned, and village life is restricted to essential local activities and occasional travel along highways kept open by snow plows.

VEGETATION

On the eastern Markagunt Plateau the plant cover is almost complete; only the volcanic cones and lava flows of very recent age and a few canyon walls are bare. In addition to the conspicuous conifers, aspens, and perennial shrubs, the flora includes a few cold-climate biannuals and such annuals as complete their life cycle during a growing season of 1 to 3 months (Pls. 2, 3, 5). Though in density of growth and grouping of species the plants conform to no system, they are roughly arranged in three zones within which certain species are dominant: the Upper Sonoran Zone, the Transition Zone, and the Canadian Zone. In the Upper Sonoran Zone, the indigenous flora is sparse and erratically distributed. In particular, juniper and pinyon, which generally in the plateau country constitute almost continuous "pygmy forests," are meagerly represented. On Pinyon Ridge, along South Creek, and in a few other places, these trees form fairly dense stands between 7,000 and 7,500 feet, but at corresponding altitudes at Gravel Pass they are substantially replaced by oak brush; on Sheep Flat by sage-brush and bitter brush; and on the slopes north of Panguitch Lake by sage-brush, manzanita, and abundant mountain mahogany. Indigenous cottonwoods (*Populus angustifolia*) are scarce; the cottonwood trees (*Populus*

fremonti) at Hatch and Panguitch are reported to have grown from seedlings brought from the Paria Valley. Willows also are rare and restricted to special places. The Transition Zone is the natural habitat of the yellow pine (*Pinus ponderosa*). At altitudes of 7,500 to 8,500 feet, this conspicuous tree grows on flat lands, ridges, and valley slopes, and even arises from cracks in the lavas. Substantially pure stands of pine cover many square miles and in places small groves and individual trees extend far above and below the usual zonal boundaries. With increasing altitude, decreasing temperature, and increasing snowfall, the dominant pines of the Transition Zone give way to the spruce and fir characteristic of the Canadian Zone—altitude 8,500 to 9,500. Throughout the Canadian and Transition zones and even in the Upper Sonoran Zone, aspen is widely distributed, and the glades are carpeted with flowering plants, including acres of the much admired columbine, larkspur, and bell flower. In late summer the brilliantly colored aspen, the dark conifers, and the grasslands dotted with flowers of various colors, combine in producing a landscape of surpassing beauty which has served as the setting for many technicolor moving pictures. Also attractive during summer time are the flower-dotted, treeless meadows along Rock Creek and Duck Creek, about Blue Springs, and in Castle Valley.

The forests of the Markagunt are sources of valuable timber. The annual yield is estimated as 4,500,000 board feet, of which about 82 per cent is yellow pine; 12 per cent Englemann spruce; and 6 per cent Douglar fir. In normal years, about 500 cords of aspen is gathered for making excelsior.

ANIMALS

During the course of field work, the indigenous mammals most frequently seen were chipmunks, squirrels, porcupines, and deer in the forested lands; woodchucks in the wet meadows, and rabbits in the more arid, treeless areas. Ring-tailed cats, coyotes, and skunks were less often seen. At Blue Springs and along Asay, Mammoth, Clear, and Bunker creeks, beavers, formerly common, are now represented by small colonies, but bear, mountain sheep, and elk, reported by the Piutes and the early white settlers, have been exterminated. More than 50 species of indigenous and migratory birds have been recorded, and forest insects are abundant. Fish, especially trout, seem to have always been plentiful in Panguitch Lake, Navajo Lake, and Mammoth, Duck, Asay, and Panguitch Creeks, a much prized source of food to the Piutes and the Mormon pioneers. During the 1880's, professional fishermen supplied the people of Panguitch, Hillsdale, Hatch, Cedar City and Parowan, and twice a week carried several hundred pounds to the mining camps at Pioche and Frisco, in Nevada.

HISTORICAL SKETCH

The earliest inhabitants of Utah, the Basket Makers, and their successors, the Puebloans, seem to have found the plateau lands north of the Pink Cliffs unsuitable for occupancy. On the other hand, the Piute clans, who for three centuries held possession of warm lowlands in the Virgin River Valley and the habitable places along the base of the Vermilion Cliffs, visited the Markagunt Plateau in the summer

FIGURE 1. LOOKING DOWN SOUTH FORK OF THE SEVIER RIVER NEAR HATCH
Streamway in Pleistocene and Recent sediments. Sevier River formation overlaid by basalt (left center); Wasatch formation in Sunset Cliffs (sky line).

FIGURE 2. LOOKING WEST OVER THE VILLAGE OF PANGUITCH
Showing style of erosion of the Sevier River formation (foreground), alluvium (middle distance), basalt (upper left), and Brian Head formation (background). Little Creek Peak (left) and Sand Creek Peak (right) on sky line.

VIEWS ALONG THE RIM OF THE MARKAGUNT PLATEAU

FIGURE 1. HARRIS FLAT
Typical of indefinitely drained unforested areas at altitudes above 7000 feet. Photograph by R. R. Woolley.

FIGURE 2. VALLEY OF DUCK CREEK
Stream terminates in sink holes in the Wasatch formation at the edge of a lava flow.

DRAINAGE FEATURES OF THE PLATEAU SURFACE

and fall to hunt the abundant deer, elk, beaver, porcupine, marmots, squirrels, and rabbits; to gather berries and seeds; and to fish in the well stocked lakes and streams. Panguitch Lake seems to have been much used by the Piutes for athletic contests and tribal ceremonies. With the colonization of upper Sevier River Valley by the Latter Day Saints in 1870–75, the annual visits of the Piutes and the less frequent incursions of small bands of Utes and Navajos came gradually to an end. Nowadays Indians are rarely seen in Garfield County.

The first white men to visit the Markagunt region were probably trappers of the period 1825–1840 in search of beaver skins. But, except for the meager report of Jedediah Smith, who in 1826 ascended the "Ashley" (Sevier) River as far as Marysvale (?), the routes and activities of these pioneer adventurers seem to have been unrecorded. So far as known, the first reliable information regarding the eastern Markagunt Plateau was obtained in 1852 by an exploring party from Parowan, which included the master scout, John D. Lee, whose grave, appropriately, is in Panguitch. A brief account of this expedition was published in the Deseret News, August 7, 1852.

For more than 10 years after Lee and his associates had called attention to the fertile lands near the mouths of the big streams that flow down the east slope of the Markagunt Plateau, no systematic attempt was made to colonize the valleys of the Upper Sevier River. In 1864 a sturdy band of farmers and stockmen from Parowan and Beaver, under the leadership of Bishop Jens Neilson, explored lower Bear Valley —which they erroneously thought to be the Sevier Valley—and made their way eastward through the Sand Peak Pass; and on April 17, 1864 camped at the mouth of "a beautiful, big stream" [Panguitch Creek] (Pl. 2). In 1866 they were driven away by the Indians.

In 1870, an expedition to explore the Paria Valley, a party of 43 men, including Major J. W. Powell, camped "at the well located and temporarily abandoned town" "on the Sevier River and proceeded up the South Fork Valley, which they described in glowing terms.[1] In 1871, after peace had been made with the Utes, the officials of the Mormon Church decided that "the time had come to reoccupy the lands beyond the mountains." On March 18 (19?) the families "called" for this enterprise arrived at the site selected by the pioneers of 1864. The interrupted activities of the abandoned "Fairview" were resumed in the newly organized village of Panguitch, for which a postoffice was established June 10, 1872.

With the founding of Panguitch began the search for suitable farm lands along the east base of the Markagunt Plateau, where water from the South Fork of the Sevier River and its chief tributaries was available for irrigation. In the summer of 1871, 15 families, under the leadership of G. D. Wilson, founded Hillsdale, in 1872, the town of Aaron, near the mouth of Asay Creek, was established by 10 families, 70 people, and farmers occupied lands in the broad valleys of Mammoth, Asay, and Castle Creeks. In 1880, the families at Aaron joined with those from adjacent settlements in founding Hatchtown, at the junction of the Mammoth and the Sevier. But after the town was flooded by the breaking of the source reservoir, a site on higher ground was selected—the present village of Hatch founded in 1900–1902.

[1] Letter by A. Milton Musser, published in the Deseret News, September 21, 1870.

A few years of experience taught the farmers that the eastern Markagunt Plateau was unsuitable for large scale agriculture. By 1880, raising of cattle and sheep had become the dominant industry, and the farms found their chief value as sources of stock feed, especially during the long winter season.

In the early days it seemed as if the natural grasses and shrubs on the eastern Markagunt Plateau could support an unlimited number of cattle, but as the herds grew in size, much of the plateau surface showed the effects of overgrazing. A further check to the expansion of the livestock industry was the establishment of the Dixie National Forest (1905), which resulted in the practical exclusion of livestock until the natural plant cover of the plateau could be restored. At the present time a strictly limited number of cattle and sheep have access to national forests and many are cared for in private pastures; the open range has relatively little value.

In the generally inhospitable environment at the base of the eastern Markagunt Plateau, the population has grown very slowly—almost wholly by natural increase—to the present 2,400 persons, concentrated in the villages of Panguitch and Hatch. Panguitch has greatly enlarged its original moderate supply of water for irrigation from Panguitch Creek and the Sevier River by converting Panguitch Lake into a storage reservoir, and thus has made possible the increase in farm lands from 300 to approximately 3,800 acres. At Hatch an irrigating ditch 7 miles long has brought about 300 acres of land under intensive cultivation, and additional crops are raised on "bottom lands" and a few dry farms. Part of the income of Panguitch and Hatch is derived from lumbering, which in late years has become highly profitable.

GEOGRAPHIC FEATURES

General expression.—In its geographic setting, the eastern Markagunt Plateau is an inseparable part of the Markagunt Plateau—a lofty, eastward-tilted earth-block whose original surface has been considerably reduced by erosion, remodeled by volcanism, and slightly modified by glaciation. As a topographic unit, the Markagunt Plateau as a whole differs little from the other six enormous flat-topped, cliff-walled rock masses that make up the District of the High Plateaus of Utah. The outstanding topographic features of the eastern Markagunt are the eastward sloping surface, the precipitous cliffs that sharply define its south rim, the volcanoes, the extensive lava flows, the disconnected level areas—locally called "flats," valleys that are broad and shallow at their heads and steep-sided farther down, and the restriction of perennial run-off to a few streams, most of which rise in springs of large flow. Outcrops of sedimentary rocks show average altitude of the plateau as approximately 8,000 feet; the altitude of considerable areas northwest of Panguitch Lake is 9,000–9,500 feet, and a narrow strip along the Sevier River is 6,500–7,000 feet. Above the plateau surface, several volcanic knolls rise 300 to 800 feet, and just west of the area mapped (Pl. 1) Houston Mountain attains an altitude of 9,200 feet, Hancock Peak, 10,500 feet, and the lava-capped Brian Head, 11,315 feet.

The south rim of the eastern Markagunt marks the common boundary of two strongly contrasted topographic patterns. From a narrow zone of interlaced gullies, Seaman, Stout, and Dairy creeks with gradients exceeding 600 feet a mile carry surface waters down precipitous inclines to the Parunuweap and Virgin Rivers and

on to the Colorado River, through a region of remarkable ruggedness. On the other hand, with few exceptions, the streams that flow northeastward from the plateau rim to join the slow-moving South Fork of the Sevier River cross little-dissected slopes in shallow, generally broad valleys, and those that trend eastward and northward down the regional slope of the Markagunt—some of them in canyons—have relatively slight gradients (Pl. 3). Thus, the average gradient of Castle Creek is approximately 75 feet a mile; of Asay Creek, 50 feet; of Mammoth Creek, the longest stream, 90 feet; of South Creek, 50 feet; of Rock Creek, 100 feet; and of Panguitch Creek, 110 feet.

Since the eastern Markagunt Plateau attained its height and structural attitude, the rate and manner of erosion of its surface has been governed chiefly by the extent and relative hardness of the various igneous and sedimentary rocks underlying it; the volume and gradient of streams have been subordinate factors. Consequently, parts of the plateau surface remain substantially intact and other parts are so fully coated with recent lavas as to conceal the pre-existing land forms. Where the reduction of the plateau surface has not been impeded by the extrusion of lavas, the relatively soft sedimentary rocks have been modeled by streams into long ridges capped by mounds, and broad, flat-floored valleys with steeply inclined walls, some of which present the stairlike profile characteristic of slopes developed in horizontal strata of variable hardness. In the least resistant rock, long continued weathering and stream scour have produced the forests of columns and pinnacles that characterize the White Tops, the borders of Hatch Mountain, and upper Castle Valley (Pl. 5, fig. 2).

Drainage.—Of the streams that drain the eastern Markagunt Plateau, some are perennial, many intermittent, and many more ephemeral. Swain Creek, Panguitch Creek, Mammoth Creek, tiny Castle Creek, and the two forks of Asay Creek are through-flowing branches of the Sevier River. Tommy Creek, Duck Creek, and Three Mile Creek are permanent streams, and in normal years Haycock, Butler, and Pole creeks carry a little water throughout most of their courses. Of the tributaries to Panguitch Lake, Blue Creek and the smaller Bunker and Clear creeks are perennial. The long Strawberry Creek, Lime Creek, Rock Creek, and the streams that traverse Coalpits Wash and Spring Hollow illustrate the intermittent streams that derive their short stretches of flowing water from springs or saturated meadows at their heads and farther down valley.

Like the intermittent streams, many short and most of the long perennial streams, except Panguitch Creek which rises in Panguitch Lake, head in clear, cold springs that emerge from definite orifices in walls of sedimentary rocks, at the base of lava flows, or in areas of concentrated seepage. The accompanying table, which lists measurements made by Elmer Butler, U. S. Geological Survey, Table 1, suggests that fluctuation in the flow of the major springs is in accord with the trend of changes in regional climatic conditions, but the volume of spring water in any given year seems to correspond roughly with the precipitation of the preceding year. This lag of 10–15 months suggests that, though some of the underground channels are well defined, most of them are unsuitable for the rapid passage of water from sink hole to outlet apertures. Thus in 1926 when the yield of Duck Spring was fully twice the annual

average the precipitation at Panguitch was about half the average. In 1917 the year of maximum flow of Blue Spring (12.8 second feet) the rainfall at Panguitch was near the all-time low. In 1946 the meager flow from several springs corresponded in time with precipitation exceeded only twice in 40 years. As feeders for streams, the

TABLE 1.—*Hydrologic data: eastern Markagunt plateau*

	October 8, 1944	October 8, 1945	September 16, 1946
Flow of springs in second-feet:			
Duck Creek	16.4	7.72	3.97
Blue	5.16	5.07	4.60
Mammoth	9.00	8.57	5.45
Upper Asay	8.60	5.47	3.31
Lower Asay	26.3	19.80	18.30
West Fork Asay	1.07	0.42	0.13

	1943	1944	1945	1946
Run-off in second-feet:				
Sevier River at Hatch	105	142	119	76.70
Precipitation-annual:				
Panguitch	9.28	7.61	6.66	12.18
Hatch	9.35	6.74	—	—
Water content of snow in inches (Duck Creek)		17.80	24.40	8.30

springs are obviously effective. It is estimated that fully 80 per cent of the water in Duck Creek, 50 per cent of that in Mammoth Creek, and nearly all that in Blue Creek comes from individual springs, and that three springs supply about 80 per cent of the average run-off of Asay Creek. Even the South Fork of the Sevier River, the master drainage channel for the eastern Markagunt Plateau and adjacent regions, is in large part supplied by well defined springs. On October 7, 1944, its measured discharge at Hatch was 82.9 cubic feet a second, of which an estimated 45 cubic feet was contributed by 5 springs in the tributary Mammoth and Asay Creeks. Above the mouth of Asay Creek Sevier River is often dry.

For an estimated half of the plateau, the streams of all classes have no surface outlets; they terminate at sink holes in the limestone and pyroclastics or at cracks in the lavas, and where such orifices are not available, form shallow ponds which evaporate during dry periods. Part of the water that enters underground channels is believed to reappear in the huge springs about the borders of the Markagunt Plateau: the sources of the west-flowing Coal Creek, Parowan, Red, and Bear Valley creeks, the south-flowing tributaries to the upper Virgin River and the east-flowing branches of Sevier River. Much of it doubtless sinks to lower levels and emerges in distant places as seeps in alluvial valley fill. Several streams that were once through-flowing suddenly disappear underground; some terminate at the edge of

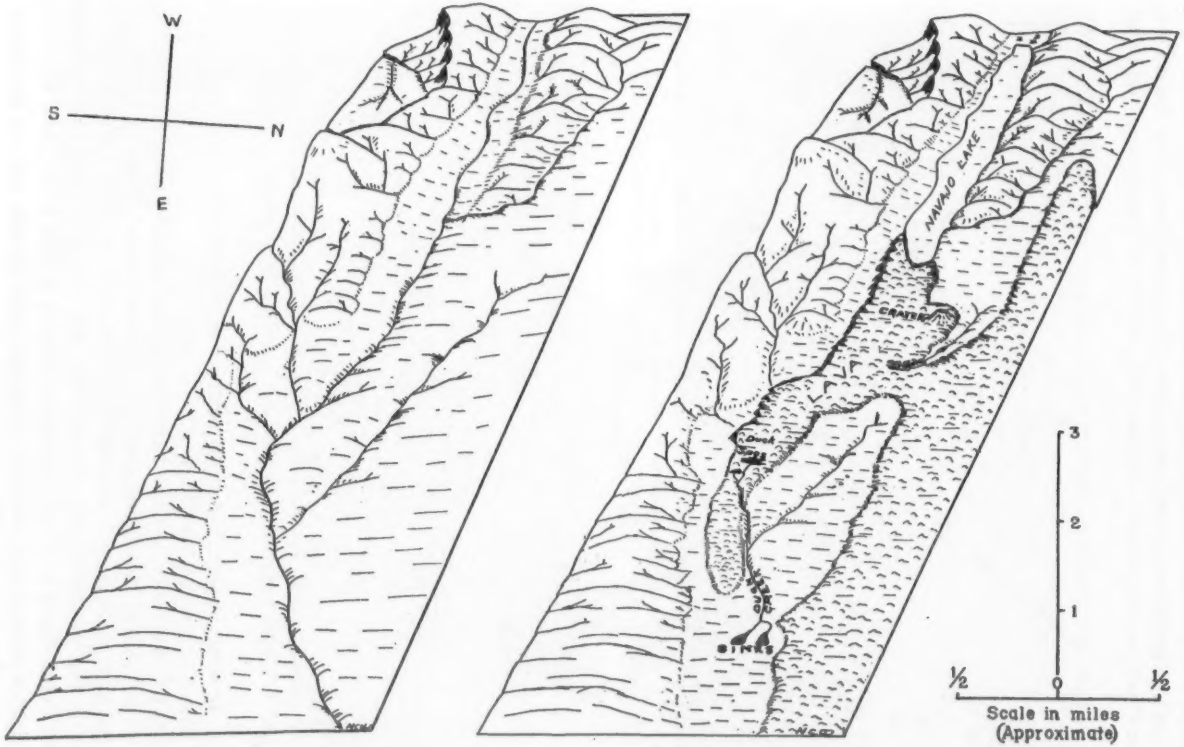

FIGURE 2.—*Sketch map showing re-adjustments of drainage in Duck Creek Valley*

lava flows, and the course of others had been interrupted by faulting (see section on Structure). Particularly conspicuous in these respects are Duck Creek, Ipson Creek, Bunker Creek, and other water courses in the vicinity of Blue Springs and Cooper

FIGURE 3.—*Sketch map showing re-adjustments of drainage in the vicinity of Panguitch Lake*

Knoll. In several places temporary obstruction by lava flows is recorded in lake beds, now choice grazing land (Pl. 4).

In Duck Creek Valley, a dam of basalt has impounded the waters of Navajo Lake. Farther down-valley the original creek seems to have been again obstructed, forming a second lake whose floor is now represented by meadow lands. Some water still makes its way beneath the lava fill, but most of it has found courses farther underground and emerging as springs and seeps forms the present Duck Creek which after a traverse of about 2 miles abruptly drops into three big sink holes on the floor of a wide open valley (Fig. 2; Pl. 3).

North and east of Blue Springs the original drainage pattern seems to have been

FIGURE 1. MEADOW NEAR THE MOUTH OF BUNKER CREEK
Bed of a lake formed by obstructing lava flows and drained by recently developed channel. Photograph by U. S. Forest Service.

FIGURE 2. EAST END OF PANGUITCH LAKE
Bordered by pyroclastics of the Brian Head formation and overlooked by lava-capped Cooper Knoll.

LAKE BASINS RECORDING RE-ADJUSTED DRAINAGE

FIGURE 1. WHITE SILICEOUS LIMESTONE (WALL) OVERLAID BY PYROCLASTICS AND UNDERLAID BY PINK LIMESTONES OF THE WASATCH FORMATION
Along Federal Highway 89 south of Asay Creek.

FIGURE 2. EROSION FORMS TYPICAL OF "THE CASTLES" IN CASTLE CREEK VALLEY

FIGURE 3. IGNEOUS AGGLOMERATES ALONG UPPER PANGUITCH CREEK

almost completely erased. Before lavas were outpoured athwart their courses, Bunker and Blue Springs Creeks were tributary to Mammoth Creek; in places through the lava fields west of Miller Knoll and in Black Rock Valley the abandoned stretches of their valleys are recognizable. Because their long used southward course was obstructed and a possible north or east course blocked by ridges of more ancient rocks, these streams were forced to pile their waters into a rock-bordered basin, whose floor is represented by the saturated Blue Springs meadows. In this basin, standing water accumulated until it reached the lowest point on the rim, a col at the head of a short tributary to the original Clear Creek. Across this easily eroded obstruction, the outlet stream rapidly deepened its channel until the ancient lake, once probably as much as 50 feet deep, was completely drained and its source streams redirected to unite with those that enter Panguitch Lake (Fig. 3).

West of Cooper Knoll the anomalous stream system at Blue Springs is substantially reproduced. Before the adjacent masses of basalt were accumulated, Ipson Creek, Clear Creek, and shorter streams seem to have poured their waters into an enclosed pond—the ancestral Panguitch Lake—which at high-water stages overflowed through Rock Creek to join the Sevier River. When lavas blocked the southern outlet, waters supplied by the long-established tributaries supplemented by the relocated Blue Creek raised the lake surface until an outlet was found about 25 feet above the existing outlet. By cutting a deep, narrow, short trench, an outflowing stream tributary to Panguitch Creek was established and progressively the lake was reduced to its present expanse and depth. An eventually complete drainage of the basin is prevented by an artificial dam, 26 feet high, which impounds water for use in irrigation. As mapped with the assistance of Elmer Butler, Joseph Andrus, and Ralph H. Falker in August, 1946, its maximum depth is 32 feet below the mouths of the tributary streams. The depression occupied by Panguitch Lake is a somewhat ancient feature of the Markagunt landscape. In origin it seems related to movements along the Clark Mountain fault, which probably predates the blocking lava flows, thus duplicating the history of Horse Lake on the downthrown side of a minor displacement. However, the age and the original topographic expression of the structural disturbance is but approximately known.

SEDIMENTARY ROCKS

GENERAL STRATIGRAPHIC RELATIONS

The sedimentary rocks of the eastern Markagunt Plateau are terrestrial deposits highly variable in composition, style of bedding, and inter-relations. Besides of sandstone of peculiar composition, lenses of conglomerate, sheets of exotic igneous gravel, and thin layers of clay shale, marl, and travertine are parts of measured sections. By far the most common are the intergrading and alternating limestones and pyroclastics.

Except for rare Pleistocene gravels, the sedimentary rocks are Tertiary representatives of the Wasatch formation (Eocene), the Brian Head formation (Miocene?), and the Sevier River formation (Pliocene?). All these stratigraphic units have been traced into adjacent regions, where they have been studied in detail; therefore, inter-

pretive descriptions of the eastern Markagunt is restricted chiefly to essential characteristics, regional relations, and local features. In a broad sense the present report supplements those prepared by Callaghan (1938), and Gregory (1944, 1945) for the Sevier River Valley, the Paunsaugunt Plateau, and the western Markagunt Plateau.

WASATCH FORMATION

On the eastern Markagunt Plateau, rocks assigned to the Wasatch formation are sparsely and discontinuously displayed. The top of the formation is exposed in the flat lands along Swain, Strawberry, and Duck Creeks; on the floors of Tyler and Castle valleys; and in the canyon walls of upper Mammoth Creek. Because the outcrops are small and their contacts largely concealed, it was impractical to define their borders. They are represented by the symbol used for the Brian Head formation (Pl. 1). It is believed, however, that the Wasatch formation, now largely buried, is co-extensive with the entire Markagunt Plateau; it is typically represented by the cliffs about its borders: the Sunset Cliffs east of the Sevier River, produced by faulting, and the Pink Cliffs at the south rim of the plateau, produced by headward erosion of the Parunuweap and Virgin Rivers. In the canyons of Stout, Seaman, and Dairy creeks, vertical walls of brightly colored Wasatch extend downward from cliffs of white Brian Head to slopes of drab sandstones and shales that constitute the Kaiparowits formation of Cretaceous age.

Wasatch outcrops are closely similar in composition, texture, and bedding, and differ in no essentials from those classed as Wasatch on the neighboring Paunsaugunt, Sevier, and Aquarius plateaus. The formation looks fairly uniform, but measured sectoins show massive beds of pink limestone irregularly interstratified with thin, hard, calcareous beds of various bright colors, lenticular gray sandstone, and conglomerates. Firmly embedded within the massive limestone are many calcareous and siliceous concretions and sporadically distributed pebbles of quartz and quartzite. Most of the limestone is roughly bedded and solidly compacted, but in places it is coarsely or minutely brecciated or displays the texture of travertine. Most of the conglomerates lie at the base of the formation—the unconformable contact of Tertiary and Cretaceous rocks—and consist chiefly of polished, spherical, ovate, and discoid quartzite pebbles, 1–3 inches in diameter. The source and mode of transport of this conglomerate is highly conjectural. In composition it is entirely unlike the coarse material in the Brian Head formation that overlies the Wasatch; in fact, no similar rock appears at other horizons in the Tertiary of south-central Utah.

Though beds classed as Wasatch in the present report are Tertiary, doubtless Eocene, neither their fauna, their physical features, or their stratigraphic relations date them more precisely. In the fossil fauna, Reeside recognized *Physa* sp., and *Bullimus* sp. "age undetermined by the fossils"; *Planorbis utahensis* Meek—"not reported below the Wasatch"; *Helix macrococyclis spatrosa* Meek and *Celliforma spirifer* Brown ?—"reported from the later Eocene chiefly". That the Eocene limestones of the eastern Markagunt are not the oldest Tertiary is shown by evidence of erosion in this region while as much as 2,000 feet of Tertiary strata were being laid down in other parts of Utah; a stratigraphic hiatus of 1,000 to 5,000 feet in the southern High Plateaus is represented in the Wasatch Plateau by an uninterrupted sequence of late Cretaceous, Paleocene, and Eocene beds.

BRIAN HEAD FORMATION

General features.—In the southern High Plateaus of Utah, the Wasatch formation generally is overlaid by the Brian Head formation and in turn by andesitic lavas. These units are thick, distinctive in color and, in consequence of faulting and erosion, are displayed on a magnificent scale. Thus the pink-red Wasatch and creamy white Brian Head make up the stupendous Table Cliffs of the Aquarius Plateau and a large part of the lofty Pink Cliffs that wall in the Paunsaugunt and the Markagunt plateaus, the Sunset Cliffs along the Sevier River, and some of the spectacular features of Bryce Canyon National Park and Cedar Breaks National Monument. On the eastern Markagunt Plateau, where not concealed by lavas, the Brian Head forms almost the entire surface; its prevailing white color in a region dominated by red, gray, and black rocks makes it conspicuous on canyon walls, ridges and peaks, and in weathered mounds at the base of cliffs. In the present rough topography the formation is traceable westward to the rim of the Markagunt Plateau, northward to upper Bear Valley, eastward across the valleys of the upper Sevier River, and southward to the crest of the Pink Cliffs, beyond which it doubtless once extended into regions now occupied by Mesozoic rocks. Throughout an area of about 1500 square miles the Brian Head occupies a common stratigraphic position and exhibits the same range in texture and composition. Its style of bedding and physical make-up on the Markagunt Plateau are substantially duplicated on the Sevier and the western Aquarius Plateaus. (Gregory, 1944, 1945)

In South central Utah, the Brian Head formation generally comprises two strongly contrasted stratigraphic subdivisions. The lower subdivision consists chiefly of white, fine-grained, uniformly stratified limestone and pyroclastics; the upper of dark-gray, remarkably coarse agglomerate. Along the westward-facing cliffs of Sevier Plateau, where the entire formation is exposed—typically in Limekiln Gulch and at Casto Bluff—the calcareous and tuffaceous rocks are separated from the agglomerate by an erosional unconformity believed to be regional in extent and to record a significant event in geologic history, though not so clearly shown on the eastern Markagunt. The persistence of this time break over large areas has led to the suggestion of Callaghan (personal communication) that the Brian Head formation be restricted to the stratified beds and agglomerate correlated with the "Bullion Canyon volcanics" of the Tushar and northern Sevier plateaus.

Stratigraphic and lithologic features.—The rocks that make up the lower division of the Brian Head formation are everywhere stratified and include calcareous, arenaceous, and pyroclastic beds that maintain no consistent positions or topographic characteristics. Where they consist almost wholly of siliceous limestone or volcanic ash, the cliffs are sheer and glaringly white (Pl. 5, fig. 1). Those along Asay and Mammoth creeks are attractively banded in accord with their component materials: gray sandstone, yellow claystone, light-red and white limestones (Pls. 5, figs. 2, 3). Much of the true limestone, particularly that south of Mammoth Creek, is lacustrine. Most of its beds are very thin: some have the delicate layering characteristic of travertine; others, however, are massive and in places resemble lithographic stone. Associated with these dominantly calcareous rocks are thin-bedded siliceous limestones of which quartz grains in places constitute as much as 35 per cent. Of beds classed as sandstone, some are aggregates of siliceous grains in a calcareous groundmass,

others show calcite only as cement. In these rocks, the most common pebbles and microscopic grains are angular or subrounded fragments of clear quartz, chalcedony, chert, and jaspar, in places intermingled with geodes, calcite concretions, mud balls, and tiny slabs of shale and dense limestone. This assemblage of exotic materials is radically unlike the conglomerate that characterizes the Wasatch—large, smoothly round cobbles of varicolored quartzite.

The pyroclastic constituents of the Brian Head, like the limestones and sandstones, are highly variable in thickness and content, and as stratigraphic units are distributed in a seemingly capricious manner. They include rhyolitic, andesitic, and basaltic (?) tuff—some of it welded—and scattered sheets of volcanic ash. Much of the tuff is fine-grained and regularly stratified and consists chiefly of andesine, labradorite, quartz, magnetite, biotite, and fragments of quartzite and basic lavas. Generally associated with these materials are chalcedony in abundance, rare glass shards, bits of granite, sandstone, and clay. Disintegration of the rock produces the conspicuous "green sands" which are colored by varieties of chlorite.

Northwesterly across the eastern Markagunt, the limestones in the Brian Head are increasingly siliceous and more commonly are interbedded with sandstones composed chiefly of igneous fragments; the tuff becomes thicker and generally coarser, and most of the volcanic ash lies north of Panguitch Lake. However, petrographic records and measured sections show this transition from dominant limestone to dominant pyroclastics as progressive only in a broad sense. South of Gravel Pass the rocks assigned to the formation consist almost wholly of calcite, elsewhere on the eastern Markagunt Plateau many outcrops show essentially pure limestone in association with siliceous limestone, igneous sandstone, even decomposed tuff. Limestones of various composition make up about two-thirds of Birch Mountain and less than one-third of Horse Cliffs—2 miles distant; about Burrow Flat, strata composed of calcite (95+ per cent) underlie and overlie those composed of siliceous grains (90+ per cent); and as far north as the mouth of Blue Creek, limestone found suitable for the manufacture of plaster adjoins tuffs. The sandstone and siliceous limestone commonly lie at the base of the formation, but no other rocks occupy regionally persistent places above them. This remarkably unsystematic distribution of material in strata that, in broad view, seem normally arranged implies contemporary deposition of various classes of sediments at irregularly repeated intervals. It suggests a land surface characterized by wide shallow valleys and local basins suitable for ponding water and a climate unfavorable for maintaining through flowing streams. The sources of the dominantly fluviatile and lacustrine deposits and the rare chemical precipitates in the Brian Head formation is imperfectly known. Possibly some of the basal, highly calcareous beds may represent a special phase of Wasatch deposition or be the product of disintegration and redeposition of the Wasatch, but the peculiar sandstones and the abundant quartz and igneous fragments in the siliceous limestones obviously came from outside sources; no similar rock lies below them on the Markagunt Plateau, nor in regions east, south, or west. They are believed to represent ancient lavas and intrusive rocks at such volcanic centers as Little Creek and Bear Valley Peaks.

In southern Utah the agglomerate that constitutes the upper part of the Brian Head formation is substantially co-extensive with the Sevier and northern Aquarious plateaus and, on the Markagunt Plateau, is prominent in cliffs and outlying masses, particularly in regions tributary to Panguitch Creek. Unlike the widely variable and irregularly distributed limestones, sandstones, and pyroclastics that lie below it, the agglomerate has everywhere much the same composition and texture. In Panguitch and Clear Creek valleys, the agglomerate consists chiefly of cubical and rectangular blocks of compact, scoriaceous, and porphyritic andesite intermingled with small fragments of rhyolite (?), ash, and sandstone (Pl. 5, fig. 3). On upper Sheep Flat, it disintegrated into angular, slightly weathered blocks of various sizes, and still farther south, on Hatch Mountain and adjacent highlands in valleys tributary to Mammoth Creek and Sevier River, is represented by coarse gravels. The source of the materials of the agglomerate and the forces that carried them to their present resting place are unknown. However, it is probably significant that northward toward the volcanic Tushar Mountains, this peculiar rock increases from less than 100 feet to more than 1,000 feet thick. Though much of its mass is similar in composition to the lavas that overlie it, there seems no reason to assume a common origin; it is believed that the agglomerates, in places true volcanic breccia, represent lava that predates the andesitic and rhyolitic flows.

Age Relations.—The position of the Brian Head in the geologic time scale has not been established: the rare fossils—undetermined species of *Unio*, *Bullinus*, *Physa*, and *Planorbis*—range throughout the Tertiary of southern Utah. As the formation is overlain by the Sevier River formation of Pliocene or early Pleistocene age, and the underlying Wasatch of the Markagunt Plateau is probably of fairly late Eocene age, a tentative assignment to the Miocene seems in accord with the stratigraphic relations and the known history of volcanic activities of the Colorado Plateau region. But the evidence for this assignment is far from satisfactory. Generally at the contact of the Brian Head and the Wasatch, red, massive, thick-bedded limestone typical of the Wasatch lies immediately below white, thin-bedded siliceous limestone or volcanic debris. In Castle Valley the basal Brian Head is consolidated silty sandstone penetrated by tubes, once occupied by trees. However, conglomeritic lenses similar to those that characterize the basal Brian Head appear in the uppermost Wasatch, and no regional hiatus indicative of a long pause in sedimentation has been demonstrated. This gives some basis for the suggestion that the Brian Head is a phase of Wasatch deposition—"pink Wasatch" capped by "white Wasatch." The unconformity between the Brian Head and the overlying Pliocene (?) Sevier River formation records a major time lapse; it is believed to represent a widespread surface of erosion on which, after regional uplift, the ancestral Colorado drainage system came into being. Dissection of this surface has proceeded so far that the Miocene (?) and other Tertiary rocks have been preserved only where reinforced by thick resistant lavas and compact agglomerates. Whatever its precise place in the time scale, the Brian Head formation predates the regional large-scale faulting of late Tertiary and early Quaternary times, and its pyroclastic beds are the oldest volcanics in the southern High Plateaus: sheets of rhyolite, andesite, and basalt lie above the formation, and the rare dikes pass through it.

Petrography.—Field and laboratory study of the rocks that make up the Brian Head formation permit the recognition of five classes: 1. True limestone; calcite 98+ per cent; includes travertine, oolite, and lithographic rock. 2. Siliceous limestone; calcite, 70± per cent. 3. Calcareous grit. 4. Silicic vitreous tuff. 5. Agglomerate.

With a view to tracing the probable sources of their components, many rocks of these classes were studied in thin section, and because of their unusual composition the following seem worthy of record. The first six listed were described by Professor Bronson Stringham, University of Utah, the seventh by Clarence S. Ross, I. S. Geological Survey.

Breccia. Upper valley of Three Mile Creek. 1. Angular fragments of andesite and hornblende basalt. 2. "White sandstone"; thinly, evenly bedded; composed principally of closely packed, medium-size, clear quartz grains; small amounts of magnetite, hornblende, and feldspar. 3. Green sandstone, irregularly stratified; consists of fairly well-rounded quartz grains 0.25 to 0.5 mm. in diameter, magnetite (10+ %), and inconspicuous feldspars and hornblendes. The greenish color is due to chlorite, which appears to cement the grains.

Igneous grit. East shore of Panguitch Lake. Generally gray; coarse and fine angular grains cemented by a little silica and much iron oxides; includes quartz, feldspar, biotite, muscovite, hornblende, a little magnetite, and fragments of quartz sandstone. An abundant constituent is rounded grains of black volcanic glass.

Tuff. Near mouth of Pole Creek, at base of lava flow (andesite?). Much glass with fragments of quartz, biotite, feldspar, hornblende and igneous rock.

Conglomerate. Upper Bunker Creek. Fragments and grains in order of abundance: quartz, siltstone, feldspar, igneous rock, jasper, chalcedony, and clay. In near-by places is a pink tuff breccia: quartz, biotite, feldspar; calcite cement and fragments of rhyolite in a matrix of porous glass.

Sandstone and limestone lenticularly interbedded. Road cuts west of Gravel Junction. 1. Calcareous sandstone. Clastic calcite grains 1 mm. to 0.5 mm. in diameter, and calcite cement (about 35%); subrounded to roughly angular fragments of clear, white, pink, and brown quartz (35%), orthoclase slightly kaolinized (10%), black, gray and white chalcedony and considerable clay material; includes some rounded fragments of red quartzite and gray chert. 2. Limestone. White, compact, consistently dense; calcite 90–98 %. Six samples studied differ principally in the content of clastic grains—quarts, chalcedony and feldspar; no glass shards or diatoms. One specimen contains lenticular chert.

Tuff. West base Little Creek Peak. Composed of devitrified glass shards and angular fragments of andesine feldspar quartz and pyroxene, the latter in very small amounts. Abundance of well-preserved shards. Between the shards and mineral fragments are streaks and irregular patches of chlorite, and chlorite is present within some fragments and shards. The index of the green mineral is that of clinochlore. The rock is poorly cemented, which probably accounts for the term "green sand" used by Dutton.

'Green sandstone". Lime Kiln Gulch—east of Panguitch. The green rock from Lime Kiln Gulch is composed dominantly of volcanic rock minerals, among which plagioclase is dominant. This is associated with small amounts of brown hornblende, biotite, and magnetite. Detrital quartz in well-rounded grains, and fragments of limestone represent non-volcanic materials which form around one-third of the rock. There is an almost total absence of potassic feldspars, and the plagioclase is calcic, some of it being sodic labradorite. The character of the feldspars indicates that these were derived from andesitic rocks, and this is confirmed by the presence of andesitic rock grains. A green, secondary material forms films around the mineral grains. Chemical tests show that this is a potassium mineral and this together with a moderately high birefringence, indicates that it is essentially similar to celadonite in composition.

SEVIER RIVER FORMATION

On the Markagunt and adjacent plateaus, the thick accumulations of gravel and sand that rest on the deeply eroded surface of the Brian Head formation and underlie basalt in places are tentatively assigned to the Sevier River formation, typically exposed in the region north of Marysville, Utah, where diatoms and gastropods establish its age as Pliocene (?) or lower Pleistocene (?). Generally its beds are so poorly consolidated as to break down readily into debris-coated mounds and ridges; their features are fully displayed only at new gravel pits and road cuts. (Pl. 6.) As exposed along Federal Highway 89 between Hatch and Panguitch, it consists of roughly interbedded conglomerate, fine-grained sand, and impure clay. The coarser beds are made up largely of subangular fragments of andesite, basalt, and quartzite, some as much as a foot in diameter, set in a groundmass of similar composition. The finer beds are dominantly quartzose, but include fragmentary hornblende, mica, magnetite, chert, and chalcedony, hardened clay, and rare bits of volcanic ash. The material in the Sevier River formation is characteristic of alluvial fans and talus slopes, and its regional distribution suggests that it was transported by streams of fluctuating speed and volume, and came to rest in the nearest available depression.

STRATIGRAPHIC SECTIONS

SECTION 1.—*Swapp Point, Castle Valley*

Coarse gravel, largely composed of igneous fragments.

Brian Head formation

	Feet
8. Sandstone, light gray, calcareous; irregularly overlapping lenses 1–8 inches thick; angular and subangular grains of clear quartz, jasper, chalcedony, biotite, hornblende, and feldspar, cemented by calcite; includes irregular masses of coarser material with scattered fragments of quartz, quartzite, and shale ¼–½ inch in diameter. Contact with No. 7 sharply drawn on a wavy surface as if coarse sand had been carried over beds of lake clay; forms a cliff	25
7. Siltstone, generally soft, light yellow, amorphous, fractured, and in places crumpled. Microscope reveals calcite 85%, chalcedony 7%, orthoclase and acid plagioclase 2%, clastic quartz, hornblende, muscovite, and apatite (?) 5%	3
6. Sandstone, yellow brown on freshly broken surfaces; medium-sized subangular grains partly coated with hematite; composition much like Nos. 1 and 3	110
5. Limestone, white, tinged with red; poorly bedded, in part brecciated; composed of calcite 95+%, clear quartz and brown concretionary clay; includes fragments of limestone, irregular masses of chalcedony, and thin lenses of calcareous shale; forms cliffs decorated with white towers and pinnacles of fantastic shape—the "Castles" of Castle Valley	80
4. Sandstone, pink spotted with dark brown, fine grained, principal constituents quartzite, quartz, feldspar and clay pellets 0.05 to 2 mm. in diameter, embedded in a calcareous groundmass; color produced by disseminated hematite	4–8
3. Sandstone, gray speckled, fine grained, composition like No. 1; very resistant; forms prominent low cliffs and broad platforms	6
2. Limestone or calcareous sandstone, generally light red, thinly irregularly bedded; forms slope largely covered by debris	12
1. Sandstone, gray, compose of subrounded grains of quartz, chalcedony, red jasper, black jasper, and feldspar 0.2–2 mm. in diameter; cemented by calcite. Conspicuous are numerous circular pits, tops of vertical and branched tubes—records of ancient trees—that extend almost through rock and on eroded surfaces appear as flutes. Knobs of coarse sandstone like No. 1 are believed to mark base of Brian Head formation	4
Total thickness measured	245

SECTION 2.—*Asay Creek Valley, 2+ miles below the mouth of Strawberry Creek*

Gravel chiefly of igneous fragments: in near-by places, basaltic lavas.

	Feet
Brian Head formation	
4. Limestone, white, mostly in thin, fairly regular beds, some closely resembling travertine; in places massive and seemingly amorphous; densest parts include vugs lined by calcite. Microscope reveals scattered oölitic structures. Forms a steep slope, upper part vertical	70
3. Sandstone, yellow brown on weathered surfaces; highly calcareous; generally thin, fairly regular beds; friable; in composition similar to No. 1. Forms broken slope.	187
2. Limestone, white; thin, dense beds; scaly, glistening beds; and massive, coarse-textured, lenticular beds; includes chalcedony, chert, quartz grains, geodes, and calcite concretions; forms a steep slope on which more resistant parts stand as irregular knobs	180
1. Sandstone, gray speckled with black; coarse grained; overlapped by lenses of lime-cemented pebbles ¼–1 inch in diameter—chiefly subangular quartz and jasper—and slabs of shale and pink limestone. Forms a bench bordered by conspicuous cliffs which exhibit fluting	3–8
In the broad valley below No. 1, rise mounds of pink limestone that probably represent the Wasatch formation.	
Thickness measured	415

SECTION 3.—*North slope of Birch Mountain*

Measured by Bronson Stringham

	Feet
10. Andesitic agglomerate; forms resistant caprock	16+
9. Limestone, white, dense, containing a little red chalcedony; has irregular fracture. Forms a prominent slope	50
8. Limestone, cream gray, white on weathered surface; thinly, fairly regularly bedded; includes a few claylike seams. Forms prominent cliff	193
7. Sandstone, buff; very fine grained cemented with lime; composed of rounded to angular grains averaging 0.2 mm. in diameter of chalcedony, quartz, small amounts of hornblende, biotite, and greenish chlorite ?	11
6. Limestone, creamy gray on fresh fracture, white on weathered surface; dense, fine grained, very thin bedded; contains much white chalcedony in veinlets and irregular chunks, as much as 1 inch in greatest dimension; limestone appears to be brecciated near top	149
5. Limestone, pinkish; fine grained to dense; includes white, irregular veinlets of calcite.	11
4. Limestone, white, dense. Resembled bed no. 8	8
3. Limestone, pinkish; fine grained to dense. Resembles bed no. 5	11
2. Limestone, white, dense; thin, hard layers. Resembles bed no. 8	6
1. Sandstone, gray; roughly, in places lenticularly, bedded; angular grains, 0.5 mm.–3 mm. in diameter, of white quartz, jasper, chalcedony, rare feldspar; includes irregular calcareous fragments and much interstitial calcite; marked by vertical pits representing tree stems and roots; rests on massive limestone (Wasatch ?). Thickness along strike	16–24
Thickness measured	469+

SECTION 4. *South face of Haycock Mountain*

Measured with the assistance of Bronson Stringham

	Feet
17. Andesitic agglomerate	20+
16. Tuff, water laid, dark gray; medium grained, composed of tuffaceous glass, subrounded fragments of chalcedony, quartz, some biotite, and a very little feldspar	11
15. Limestone, gray, dense; contains much chalcedony; bedding planes somewhat crenulated	5

14. Tuff, gray, greenish, white; generally medium grained but quite coarse near top. Includes fragments of limestone up to 2 inches in diameter, and thin lenses of limestone near bottom	138
13. Tuff, water laid, dark gray to bluish; composed principally of rounded fragments of chalcedony, red jasper, and quartz, with a little feldspar	3
12. Tuff, very white, fine grained, with a few coarse-grained fragments; very light weight; on fresh fracture resembles porcelain. An unusually pure vitric tuff	3
11. Tuff, white to light gray; medium-, coarse-, and fine-textured lenses; near top, many white veinlets composed chiefly of fibrous cellular opal, resembling fossil bone	110
10. Tuff, water-laid, rather coarse; about equal amounts of glass and crystal fragments; minerals present include quartz, feldspar, chalcedony, and an unusually large amount of biotite	2
9. Limestone, white, fine grained to dense; very thinly bedded	11
8. Tuff, grayish white, medium grained; includes chalcedony	10
7. Limestone, white; much chert near base; a few thin ash beds near top	61
6. Tuff, dirty gray; medium texture	14
5. Limestone, white; includes large irregular pieces of light-colored chalcedony	16
4. Tuff, grayish, medium grained, interbedded with white dense limestone. Limestone about one-fifth of the unit, in short lenticular beds that average about 1 foot thick. Some of the predominantly ashy material includes fragmental limestone	118
3. Tuff, dirty in color and rather coarse in texture. Weathers to grayish soil on slops.	8
2. Limestone, general gray tone, some splotches of pink; dense; considerable chalcedony near the top	36
1. Tuff, very fine grained with few crystalline fragments of quartz, feldspar, and biotite; chalcedony abundant, some masses as much as 4 feet thick and 50 feet long	6
Thickness measured	572

SECTION 5.—*Brian Head formation west base of Little Creek Peak, Bear Valley*

Measured by Norman C. Williams

	Feet
Rhyolitic lava forms top of plateau.	
9. Basic lavas, decomposed—a soil surface	4
Unconformity	
8. Tuff, green, fine grained, poorly cemented, minutely stratified; microscope reveals well preserved devitrified glass shards and angular fragments of andesine, feldspar, quartz, and some pyroxene. Between the shards and mineral fragments, and rarely within the glass, patches of clinochlore give color to the rock. In the glass, index of refraction is slightly below balsam, suggesting original andesite	32
7. Limestone, white, siliceous, homogeneous, includes thin bands of chalcedony. Microscope reveals chiefly granular calcite associated with tiny particles of quartz and feldspar. Superficially resembles volcanic ash but lacks glass shards	43
6. Conglomerate, brown; closely packed igneous boulders that average about 8 inches in diameter, the largest 2 feet	63
5. Conglomerate, gray brown, in compact beds 3–5 feet thick, interstratified with poorly cemented gray sandstone beds. 1–2 feet thick; pebbles, well rounded fragments of acid and basic lavas ½–3 inches in diameter	30
4. Same as No. 1	16
3. Sandstone, brown, evenly stratified, poorly cemented; some fine cross-bedding	15
2. Sandstone, light gray, fine grained, evenly stratified; poorly cemented	27
1. Rhyolitic tuff, red, finely stratified, fine grained; includes lenticular aggregates of igneous pebbles 2–3 inches in diameter. Microscope reveals subrounded grains of quartz, chalcedony, and glass cemented by hematite, probably secondary. Some of the glass and chalcedony fragments shard shaped. Contact with the Wasatch formation concealed	38
Total exposed	268

IGNEOUS ROCKS

GENERAL RELATIONS

As mapped by Dutton (1879), the igneous rocks of the eastern Markagunt Plateau are trachytes and basalts which occupy indefinitely outlined, disconnected areas, and in places are superposed. The trachytes were recorded as the southward extension of the lavas that cap the Sevier, Aquarius, Awapa, and Fish Lake plateaus, and the basalts as the products of local volcanoes. Dutton recognized that the basalts are younger than the trachytes and were extruded at two widely separated periods, and that probably in the interim many volcanic cones were destroyed and some of the older basalt flows were dissected by streams. He was particularly impressed by the lavas in the vicinity of Panguitch Lake—the area within which his investigations were centered. "Just south of Panguitch Lake are a number of streams which so far as appearance is concerned might have been erupted less than a century ago. The cones are perfect and the lavas not faded by time."

Recent surveys confirm the conclusions of Dutton that extrusive volcanics of two principal types cover large parts of the eastern Markagunt Plateau; that the oldest lavas (andesites) are best displayed on the slopes west of Panguitch Creek; that the youngest lavas (basalts) are especially prominent along the south shore of Panguitch Lake; that the approximate source of most basalt flows is revealed in the topography; and that the origin of the andesites is conjectural. Supplementing Dutton's observations, maps prepared for the present report show five well-defined volcanoes, large areas of old and new basaltic extrusives, and several low domes where upwelling lavas formed no craters. Furthermore, field work demonstrates that along South Creek the basalts overlie the andesites and at the western end of Prince Mountain probably overlap the edges of rhyolitic flows; that in many places the youngest basalts rest on those of greater age; but that generally the three types of lavas occupy separate districts. The rhyolites lie west and northwest of Horse Lake and are best represented along the west rim of the Markagunt Plateau in eastern Iron County, beyond the border of the present map. Little Creek Peak (altitude 10,135 feet), the stump of a huge volcano that appears to mark the site of the oldest volcanic activity in the Markagunt region, was doubtless a fountain head for rhyolitic, probably also andesitic, lavas. In the peak and particularly near its base, fractured masses of rhyolite, andesite, and pyroclastics, lie in seeming disorder. From this ancient volcano eastward, about the headwaters of Pole, Butler, and Haycock creeks, the rare outcrops of compact porphyritic andesite and agglomerate are surrounded by coarse gravel composed of various acidic and basic igneous rocks—including obsidian-gray tuffs, and varicolored ash. Generally, in this area, mapped as "undifferentiated volcanics", the relations of the intrusions, extrusions, and pyroclastics are less complex but still are difficult to determine; adequate treatment calls for studies beyond the scope of reconnaissance surveys. The basalts with minor exceptions lie south of the rhyolites and andesites; the valley of Mammoth Creek is the common boundary of two volcanic sub-provinces. North of it basalts are meagerly represented; south of it, across the Markagunt Plateau, the Kolob and Little Creek terraces, the Uinkaret Plateau, and on to the Colorado River, basalt forms the volcanic cones and the widely spread fields of lava.

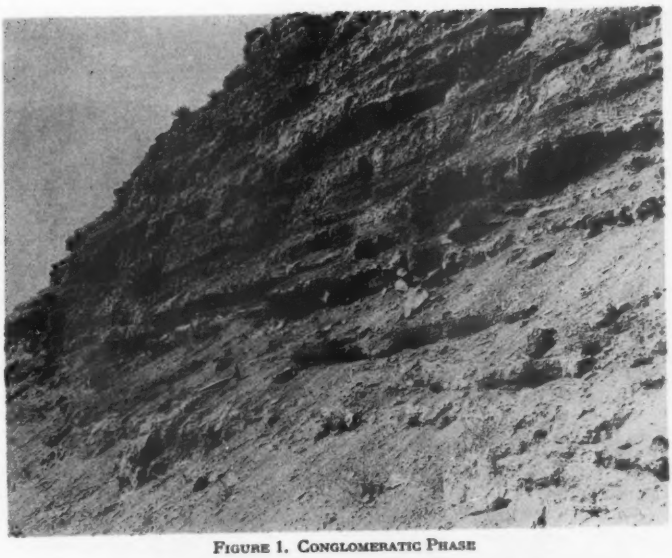

FIGURE 1. CONGLOMERATIC PHASE

FIGURE 2. ALLUVIAL AND LACUSTRINE PHASE

FEATURES OF THE SEVIER RIVER FORMATION

FIGURE 1. END OF RECENT FLOW THAT OCCUPIES UPPER ROCK CREEK VALLEY AND ERODED SHEETS OF OLDER LAVAS (UPPER RIGHT)

FIGURE 2. FLOW 6 MILES LONG IN BLACK ROCK VALLEY
It eliminated a streamway developed in rocks of the Brian Head formation.

Nearly all the igneous rocks of the eastern Markagunt are extrusives. Dikes of hornblendic basalt are plainly exposed at the White Knobs; porphyritic basalt is embedded in pyroclastics near the outlet of Panguitch Lake; and in Bear Creek and Red Creek valleys, west of the Garfield County line, vertical dikes of normal basalt cut the sedimentary rocks. An isolated knob of andesite on the floor of Pass Creek may have been the source for some of the lavas in nearby Cooper Knoll and Haycock Mountain, and dikes are assumed to be the source of the domed sheets of basalts where other sources are not recognizable.

At its upper gorge, Panguitch Creek trenches porphyritic andesites about 80 feet thick and of unknown expanse, whose origin and subsequent history were not determined. In contrast with their regionally normal position—above pyroclastics—these andesites lie below, perhaps in the midst of, tuff and igneous agglomerates. This outcrop may prove to be an intrusion or a part of a lava flow older than those that lie higher up on the adjacent Clark Mountain. The prominent joints and fractures that traverse the mass are related to the Clark Mountain fault.

TOPOGRAPHIC EXPRESSION

In the Markagunt landscape, each period of volcanic activity is associated with distinctive topographic features. On the rhyolites and porphyritic andesites, stream scour has been remarkably slow. Thus on Sheep Flats, about 25 square miles with an inclination of 2–4 degrees, stream channels are so shallow that, in general views, their courses are barely recognizable; the surface is thickly coated with igneous gravels through which, in places, small masses of pyroclastics and andesite protrude. Over the much larger and steeper slopes west of Panguitch Creek, the drainage channels worn into andesites and firmly cemented pyroclastics are also comparatively inconspicuous and include few stretches of well-defined canyons. Most of the valleys are wide-spaced and shallow, and the intervening ridges are broad, rounded at their tops, and thickly covered by igneous gravel. The only stream that, throughout its course, has cut entirely through these ancient lavas is Ipson Creek, which flows in a narrow canyon between walls of andesite. East of upper Panguitch Creek, the once widely spread sheets of andesite are represented by cap rocks of Clark and Haycock Mountains, whose south-facing cliffs stand 400 to 800 feet above the sedimentary rocks on the floor of Pass Creek Valley.

The oldest basalts, though much younger than the andesites, have been eroded much more extensively (Pl. 7). The topographically conspicuous volcanoes mapped as Asay, Bowers, and Strawberry knolls no longer retain their craters, and the lapilla, bombs, and lava streams that once formed the cones are represented by coarse-textured gravel. In such flat-floored, partly inclosed areas as Bowers, Uinta, and Grass Flats, coalescing sheets of lava remain substantially intact, and in a few other places their surface has been only slightly scoured by streams. But most of the old basalt sheets have been deeply dissected and in places partly or entirely removed. Their remnants are conspicuous as cap rocks of ridges and mesas, the rim rocks of canyons, and as isolated masses on valley floors. Especially conspicuous are the palisaded walls that record the progress of streams in grinding up and carrying away the lavas that once occupied the valleys below.

On emerging from their craters, the lavas naturally took advantage of the available

inclined runways. Some of them came to rest on slopes, but many followed the courses of streams and, as their supply of molten rock was successively augmented, filled or partly filled canyons or spread out on the broader valley floors, thus displacing or obliterating drainage channels. When the streams of lava cooled to extinction, the streams of water, confronted with the task of re-establishing their courses, developed runways at the sides of the lavas or across their tops, and from both these positions removal of the lava fill proceeded until none remained except at the top of the canyon wall. In the canyon stretches of the larger valleys, the lava has been so far removed as to permit the streams to re-occupy parts or all of their original channels. Thus Swain Creek and middle Mammoth Creek have cut entirely through the obstructing lavas and re-established the gradients of their former runways. Asay Creek has re-occupied its broad valley; all the lava has been removed from its floor, and the remnants of a once extensive sheet with a maximum thickness of about 80 feet lies high on its western rim. Strawberry Creek is trenching the lava that remains near its head, but farther down flows on sedimentary rock below a palisade of basalt. Upper Rock Creek is bordered on the north by terraced lavas 10–30 feet thick; farther down-valley, lava forms both walls of the canyoned stream, and east of Wagon Wheel Gap spreads out over slopes leading to the South Fork of the Sevier. Near its head Rock Creek has been blocked for a second time; between the rim rocks of old basalt, new basalt occupies the valley floor (Pl. 7, fig. 1). The effect of lava in guiding erosion is further shown along the course of West Asay Creek. For a mile at its head where its original channel has been obliterated by flows from Bowers Knoll, the creek is adjusted to the surface inequalities of the lava sheets. It then enters a very narrow, shallow trench cut entirely in lava, 30–60 feet thick. A short distance beyond, it substantially has completed the excavation of its valley, leaving the remains of the flow high on the north wall, and at one place on the floor. Beyond the end of the lava flow, where for miles erosion proceeded while checked at the upper end, broad flat lands adjoin the stream and the enclosing walls of sedimentary rocks have been carved into terraced slopes.

The basalts of the last general period of extrusion, though doubtless including flows of somewhat different age, have been little dissected and but slightly modified by weathering. They retain the features of fresh lava flows: pressure ridges, gas-made mounds, pits, toes, wide-open cracks, and a surface of scoriaceous blocks piled in confusion. The flows may be traced down valleys and ravines, over low divides, and around hills, and on flat lands where they abruptly end (Pl. 7). Over large areas, the huge piles of recent lava have substantially remodeled the topography by converting plains into rugged hills and re-arranging drainage. On their surfaces, streams have been unable to establish persistent runways; the water from rains and melting snows sinks into cracks or collects in ephemeral ponds. Some streams have been completely obliterated, and the course of many others largely concealed. (Figs. 2, 3). So far as observed, only Tommy Creek, which rushes down the precipitous north slope of Henry Peaks, has re-excavated its channel through the youngest lavas.

Some of the latest basalt came from definable craters at the top or on the flank of volcanoes, but much of it emerged from fissures whose positions are but approxi-

mately known. Thus the lava fields in the vicinity of Panguitch Lake and Blue Springs are unrelated in origin to Cooper Knoll and Miller Knoll—two prominent, roughly conical masses that simulate volcanoes. Cooper Knoll appears to be an outlier of Clark Mountain. Its top and a faulted block on its west side consist of porphyritic andesite; its south slope, above 8,000 feet, is formed of decomposed agglomerate that contains andesitic fragments, biotite, plagioclase, and veinlets of chalcedony characteristic of the upper part of the Brian Head formation. This material merges with the older basalt flows that form the outer walls of Rock Creek. Low down on the north slope of Cooper Knoll a small mass of scoriaceous basalt of very recent age is traceable to a local vent.

Like Cooper Knoll, Miller Knoll has the form but not the history of a volcano. Its top, its east slope, and parts of its south slope consist chiefly of scoria and fragmental tuff. Essentially the Knoll and the two adjacent smaller knolls seem to be remnant masses of Brian Head strata, and doubtless owe their preservation to caps of andesite (?) and compact pyroclastics that now are decomposed and in large part removed. From two orifices on the upper west flank, old basaltic lava was extruded. The youngest basalts, 80–300 feet thick, are piled at the north base of the Knoll, and as lava streams made rough by fracture and local distortion pass the west base and continue 3 miles to Mammoth Creek (Pl. 7, fig. 2).

PETROGRAPHY

Regarding the igneous rocks of the High Plateaus of Utah, Dutton (1879) remarks: "The petrographic work has not been embodied in this volume. Many hundreds of thin sections for microscopic investigation have long since been made—[also] a considerable number of chemical analyses." The results of Dutton's work seem not to have been published: so far as known, the rocks of the Markagunt Plateau were not studied by other members of the Wheeler and Powell Surveys, and have received but casual attention since. Accordingly during the present survey the areal distribution and interrelation of the various classes of lava were tentatively determined, and specimens thought to be representative were submitted for laboratory tests.

As recorded in field notes, the compact igneous rocks are classed as rhyolites, andesites, and basalts, and their associated pyroclastics as tuffs, agglomerates, and volcanic ash. The rhyolites are represented chiefly by fine-grained angular blocks in breccia and tuff. The andesites, some of them more appropriately termed latites, are prevailingly porphyritic and in composition exhibit no observable variation from place to place; substantially they are the rocks classed by Dutton as trachytes. The predominant basalts include fine-grained, coarse-grained, and porphyritic rocks in which olivine or hornblende is conspicuous. By far the most common igneous rock on the Markagunt Plateau is olivine basalt: essentially large and small crystals and aggregates of olivine in a microscopic groundmass of plagioclase (60+), magnetite, hornblende, and, rarely, augite. In color, mass, composition, age, and mode of weathering all the igneous rocks and pyroclastics examined are closely related to corresponding types on the near-by western Markagunt and Sevier plateaus, and generally throughout south-central Utah.

A laboratory study of the igneous rocks was generously made by Professor String-

ham. From his report on 58 thin sections—many of them essentially duplicates—the following descriptions have been selected as representative:

Andesite. Top of Miller Knoll. Contains labradorite, augite, magnetite, and a large amount of glass. Vescicles occupy about 75 % of rock.

Andesite. Brian Head (western Markagunt Plateau). An extremely dark-colored rock that because of numerous small vesicles is very light in weight. In hand specimen it probably would be called a "scoria." In thin section, numerous phenocrysts of andesine, augite, and hornblende appear, along with needles of apatite and small grains of magnetite. Commonly the magnetite is associated with the augite but is also scattered in the groundmass. The rock corresponds closely with Johnannsen's description of "pyroxene andesite", but if texture is considered important it should be called a vesicular vitrophyric pyroxene andesite.

Andesite porphyry. Panguitch-Panguitch Lake road near Sevys Ranch. Dense dark-purple rock with abundant small white phenocrysts identified as andesine. Groundmass very dense and submicroscopic.

Latite porphyry. Panguitch Lake Road, 1± mile south of Sevys Ranch. Phenocrysts are andesine and augite. Groundmass is a microscopic felted mass of very small orthoclase crystals mixed with black dust. Rock appears to have a true latitic composition.

Basalt. Mouth of Mammoth Creek. Rock as a whole is quite coarse-grained, with labradorite laths interlaced in a definite lattice network with large anhedra of feldspar between; contains a little augite and magnetite. Texture approaches diabasic.

Olivine basalt. Mouth of South Creek. Hand specimen is grayish black with a few small bottle-green phenocrysts; slightly vesicular. Olivine and labradorite form well-shaped phenocrysts in a lattice-like groundmass of small laboradorite laths between which is crowded granular augite and a lesser amount of magnetite. [Rock considered typical of olivine basalts on Markagunt Plateau.]

Olivine basalt. Clear Creek Valley near mouth of Skoots Creek. Phenocrysts are not large but quite definite and are composed of labradorite and olivine set in a dense groundmass. Fresh pyrite with slight tarnish makes up about 1% of rock; some individual masses attain a diameter, of 1½ mm.

Hornblende basalt. Northern base of Miller Knoll. Minerals in order of abundance: laboradorite augite, hornblende, glass, and magnetite. Laboradorite in large and microscopic crystals Many vesicles. [Rock closely similar in composition and texture appears in agglomerates northwest of Panguitch Lake.]

Vitrophyric obsidian. Pole Creek 4± miles above its mouth. Highly fractured glass forms the groundmass. Quartz seems to compose most of the phenocrysts with a few altered or cloudy feldspars. Many vesicles are present, most lined with a thin crust of calcite.

Acidic tuff breccia. Ridge 3± miles east of Sevy ranch. Most rock and mineral fragments are, sharply angular and less than 1 inch in diameter. They include principally pumice, quartz, feldspar, biotite, hornblende, glass, and various igneous rocks. Glass shards form the matrix. Rock as a whole is porous and poorly cemented.

Devitrified welded tuff. Mammoth Creek, near camp ground. Composed of quartz, acidic feldspar, biotite, numerous glass fragments including spheres and shards.

Microscopic study of the rocks from the eastern Markagunt Plateau revealed widely distributed andesites and basalts—old and new—but no true rhyolites. However, on the adjacent western Markagunt in the same petrographic province the predominate lava is rhyolite, and rhyolitic tuff is common.

AGE

All the lavas in the Markagunt region are younger than the Brian Head formation—tentatively considered to be Miocene. The rhyolites and andesites directly overlie

the Brian Head, and seem to be associated in origin with the agglomerate and tuff of that formation. The basalts were extruded after the more ancient lavas, the pyroclastics, and the sedimentary rocks had been deeply weathered and systematically carved by streams into canyons, steep slopes, and mountainous ridges; from volcanoes built on this rough surface, the oldest basalts flowed down valleys and spread widely over flat lands. Cessation of volcanic activity was followed by a second period of regional erosion during which the plateau surface was further reduced, the volcanic cones of the first period modified in form, the lava flows trenched by streams and in places partially or entirely destroyed. The second general period of basaltic eruption from old cones and new cones produced the basaltic piles about Miller Knoll, Cooper Knoll, and Henry Peaks, and the lava streams along Duck Creek, at Bowers Flat, in Black Rock and upper Rock Creek valleys. Bordering the Sevier River, the lavas of this last major period of extrusion unconformably overlie the Sevier River formation, considered Pliocene, and in near-by Red Creek Valley rest on the eroded surface of Pleistocene marls. At most of the source vents, the outpouring of basalts once begun seems to have continued during the life of the volcano. At some it was intermittent throughout the older, probably also the newer, cycle of activity. Thus along upper Wilson Creek two flows from a probably common source in Henry Peaks, both classed as old lavas, differ considerably in age. As masses of lava the old and the new basalts are essentially duplicates; composition and texture in a single flow varies fully as much as in flows many miles apart. Consequently, the precise correlation of widely spaced flows is impossible on the basis of mineral content. Furthermore, in many places the basalts of the first general period of extrusion are so fully covered by lacustrine silts and stream wash that their age relations are indeterminable.

The relative antiquity of the basaltic extrusions is indicated chiefly by differences of topographic setting, depth of weathering, and degree of dissection—the records of local conditions. It seems probable that volcanic activity on the eastern Markagunt began in Miocene time, continued during the Pliocene and Pleistocene, and ceased about 1,000 years ago—a conclusion supported by a study of the growth rings in the big gnarled junipers (*J. scapularium*) that rise from cracks in the newest lavas. Doctor Edmund Schulman, University of Arizona, reports, "The oldest juniper I sampled on the lava beds may with some assurance be noted as very close to 900 years old. Others in the 700–800 year class were sampled also."

STRUCTURE

As a structural feature, the eastern Markagunt Plateau is substantially the eastern part of the huge Markagunt Plateau—an earth block raised high between the Hurricane and the Sevier faults, and conspicuously tilted. Disregarding the volcanic prominences, its surface inclination averages about 2.5 degrees north-northeastward. Over areas of considerable size the dip of the stratified rocks is as little as 1 degree; on the flanks of broad low folds 4–5 degrees; and locally, 6+ degrees. On the plateau top, faults of short length, various trends, and with displacements of 1–10 feet are fairly common. Faults of undetermined dimensions are grouped at the heads of Haycock, Butler, and Pole Creek, and others less plainly expressed have disturbed

the rocks in upper South Creek Valley, Panguitch Valley, and Coalpits Wash. The walls of Ipson Canyon about a mile from its mouth are broken by two faults, with throws of 14 and 56 feet respectively, that outline a graben. Structural displacement large enough to have affected the development of the topography are features of Deedy Hollow, the west end of Clark Mountain, and the border of Horse Lake.

The Deedy Hollow fault is recorded chiefly by topographic features. It is thought to have determined the alinement of Deedy Creek—straight northward along the strike in contrast with the normal meandering streams in canyons adjusted to the regional dip. Near the mouth of Deedy Hollow and at its head, sheets of basalt west of the assumed fault trace seem to correspond with those that lie 15–60 feet higher on the east. Along the valley creek floor, horizontal discordance of strata is obvious; rocks of unlike type appear and re-appear in relations that suggest a zone of fracture.

The Clark Mountain fault is a vertical fracture of undetermined length along which andesite and bedded pyroclastics have been displaced 200–400+ feet. It is plainly shown near the head of Pass Creek where downthrown strata dipping 12 degrees west abut against those that beginning with dips of 5–6 degrees extend upward in a curve that flattens as the mountain top is approached. Northward from the Pass Creek Road, the fault is traceable for nearly a mile and probably extends much farther. South of the road, it has sheared off a segment of Cooper Knoll but seems not to have crossed the newer basalts, and probably predates them. This break in the rocks is believed to be but the easternmost of a series of fractures within a zone about 1000 feet wide along the basal slopes of Clark Mountain where, in consequence of faulting, fragmentary sheets of andesite dip in various directions, some of them west and southwest directly opposite the regional inclination of the undisturbed lavas. Farther south, variously oriented disorganized pyroclastic blocks rise higher than the lavas that normally overlie them, and some of the exposed and underwater topographic features about the east end of Panguitch Lake seem best explained by assuming that their development was guided in some degree by faulting. The difference in height of corresponding parts of an original lava sheet on opposite sides of the fault zone is estimated as 1,100 feet—the maximum displacement.

An interesting feature of the Clark Mountain fault is its apparent effect on drainage lines. It is believed that a perennial stream from the western highland once flowed through "the Pass"—a wind gap at the north base of Cooper Knoll—and that in consequence of faulting its upper part was ponded, then redirected northward at a right-angled turn. In the present topography, this once continuous tributary to the Sevier River is probably represented by the perennial Haycock Creek, which ends at "the meadows"—the floor of an ancient lake basin—and farther eastward by Pass Creek, which flows only in response to local rain storms (Fig. 3).

The Horse Lake fault displaced sheets of andesite, also the pyroclastic sediments beneath them, probably as much as 60 feet. It produced a cliff trending N 20° E, along which the courses of eastward-flowing streams were broken: their upper parts depressed and their lower parts raised. On the downthrown side of the fault, the streams followed their established channels to the west-facing cliff and, unable to cross this barrier, built up an extensive waterbody—the original Horse Lake. Debris

from the bordering highlands so raised the floor of the lake that its deepest part is now less than 10 feet below the lowest notch on the basin rim—the truncated head of the rock-walled Ipson Canyon. At high-water stages, part of the lake water escapes through this notch; the pre-fault continuous tributary to Panguitch Lake has been re-established.

The general trend of the fractures on the eastern Markagunt is in harmony with that of the master faults of the High Plateaus—their age is believed to be post Miocene. They have broken all the stratified rocks and the older lava flows; only the very youngest basalt extrusions remain undisturbed. Inconclusive physiographic evidence suggests that movement along the fault planes was intermittent and may not have ceased.

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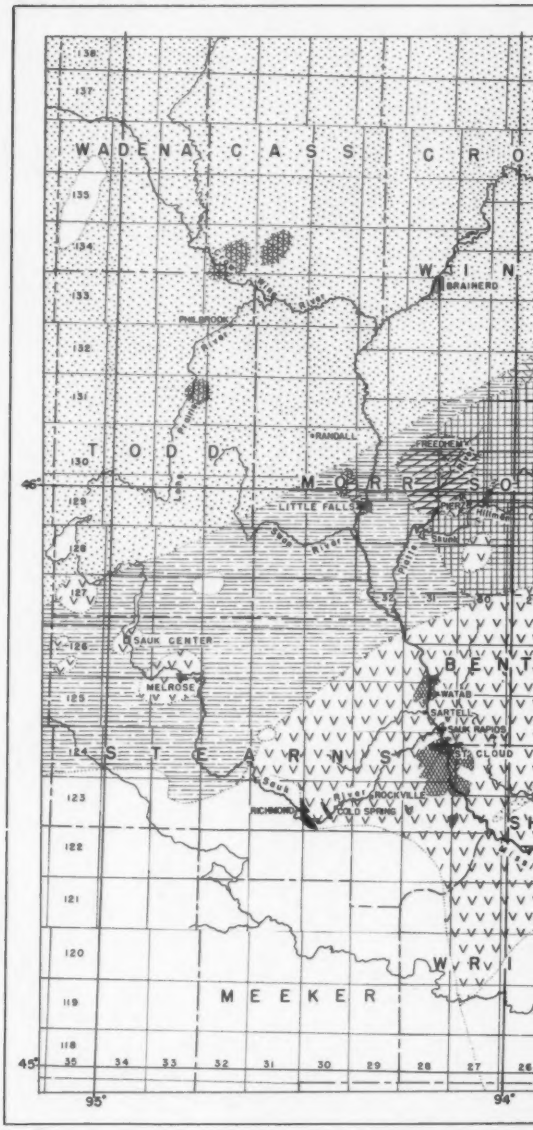
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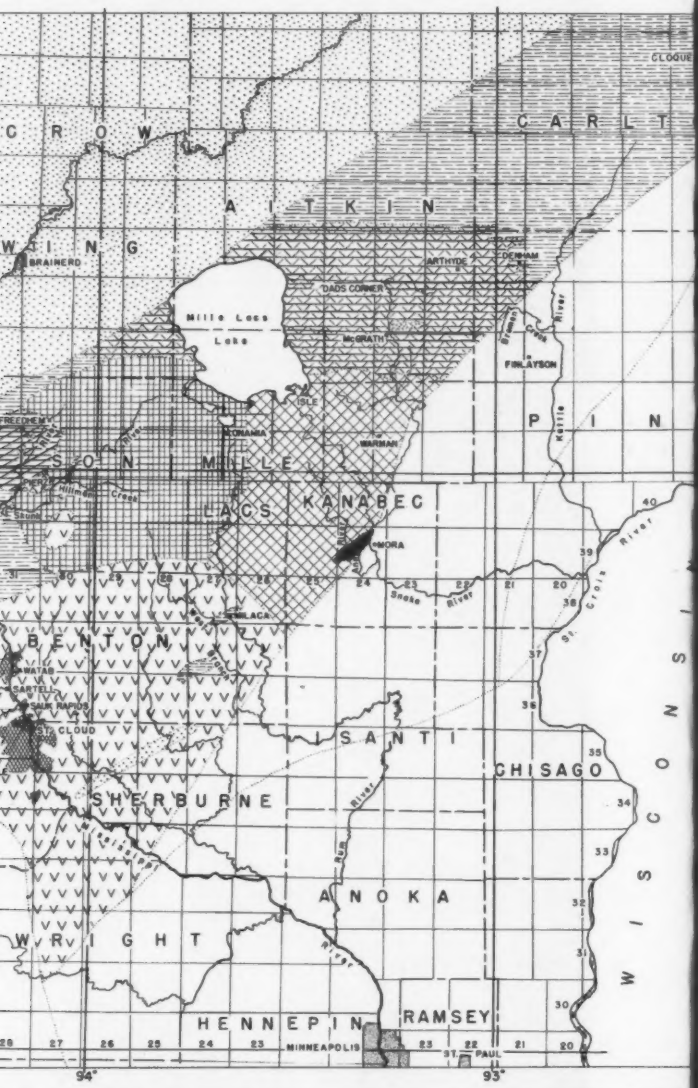

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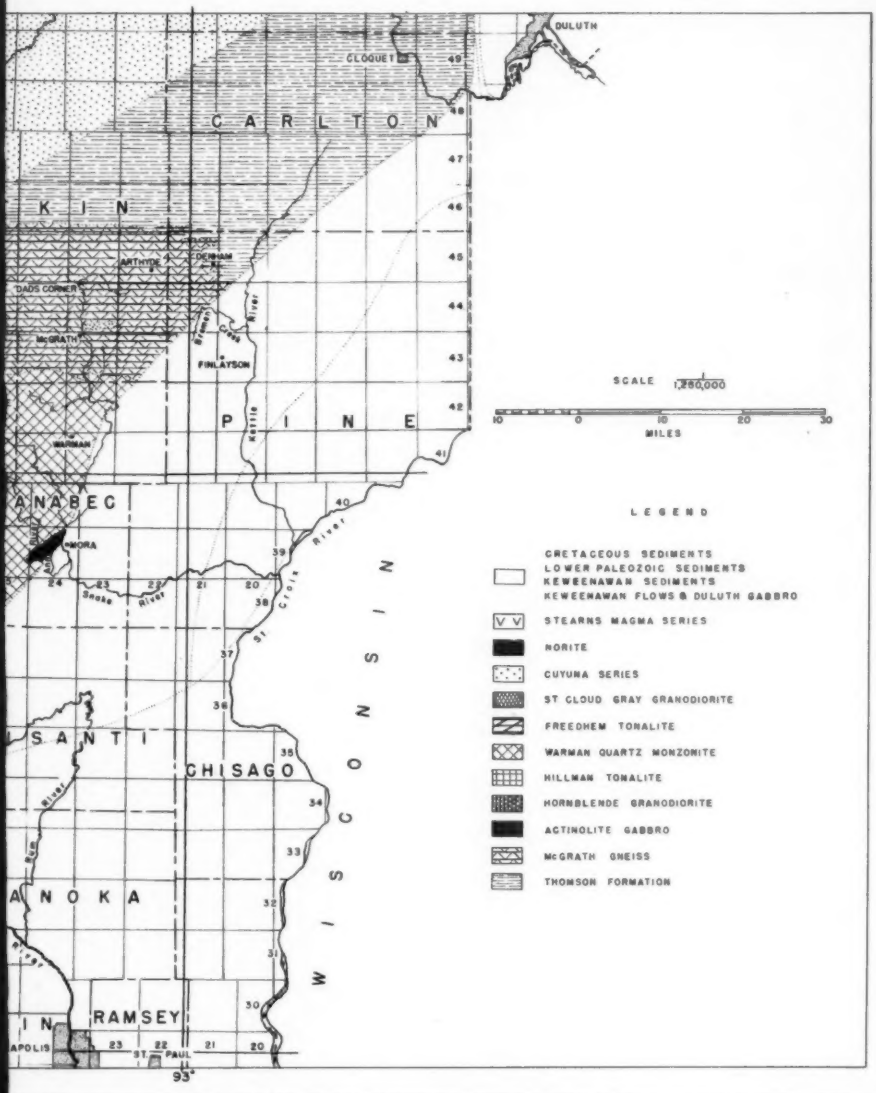

AP OF CENTRAL MINNESOTA

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INTRUSIVES OF CENTRAL MINNESOTA

BY MARGARET SKILLMAN WOYSKI

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ABSTRACT

Scattered outcrops of crystalline rock were examined within an area of approximately 3600 square miles in central Minnesota. From field data and petrographic evidence, the variety of igneous rock types can be referred to the following historical sequence: (1) intrusion of the McGrath gneiss and regional dynamic metamor-

phism (Early Algoman), (2) intrusion of a series of intermediate igneous rocks (Late Algoman), (3) intrusion of the Stearns magma series (Middle Keweenawan), and (4) intrusion of felsite and basalt dikes (Middle Keweenawan).

INTRODUCTION

This paper is an attempt to correlate and to determine the age relations of a number of scattered outcrops of rock heretofore designated as "Pre-Cambrian, undifferentiated."

The district lies in central Minnesota; it extends from Denham on the northeast, to Randall on the northwest, Richmond on the southwest, and Mora on the southeast, and includes the eastern half of Stearns County, the western half of Sherburne County, all of Benton County, Morrison County, Mille Lacs County, Kanabec County, the southern third of Aitkin County, and the northwestern quarter of Pine County. Most of this area is drained by the Mississippi River. The eastern part drains into the St. Croix River and thence to the Mississippi (Pl. I).

Individual rock outcrops are small but commonly occur in clusters of 2 or 3 acres or even in strings 2 or 3 miles long. These localities are scattered widely, separated by 2 to 15 miles of drift-covered plain. The exposed rocks are of types sufficiently distinctive to permit a limited correlation on a petrographic basis. Many exposures show contacts from which the age sequence can be deduced.

This research was supported by the Minnesota Geological Survey as a continuation of recent work on the Thomson formation and the Cuyuna iron range which adjoin this area to the north. Dr. G. M. Schwartz suggested the problem and made available plane table maps previously prepared by the survey. The field assistance by Miss Jean Stilwell in the summer of 1945 and by Miss Alberta Petersen in the summer of 1946 is greatly appreciated. Above all, the writer is deeply indebted to Dr. F. F. Grout for his advice and criticism while this study was being made.

PREVIOUS WORK

Early reports by Whittlesey (1866), Kloos (1871), and Garrison (1880) mentioned the existence of crystalline rocks in central Minnesota but the descriptions are exceedingly brief. Upham gave the first comprehensive report of the geology of central Minnesota in 1882 when he described most of the outcrops which are now known. He gave further details in his reports of 1888 and 1898. A more complete description, without correlation, was given by Harder and Johnston (1918) for eastern central Minnesota. Bowles (1918) carefully described the igneous rocks which are quarried in central Minnesota. Thiel and Dutton (1935) also described the quarry rocks of central Minnesota.

Thorough descriptions of some central Minnesota rocks with both petrographic and chemical analysis were made by Streng and Kloos (1877). Wadsworth (1887) and Krum (1935) gave petrographic and chemical analyses of the St. Cloud Gray granodiorite; Grout (1908) gave a similar report for the major rock types of Stearns County. A detailed petrographic description without chemical analysis of the St. Cloud Red granite was made by Krum (1935), of the Rockville quartz monzonite by

Tatge (1939), and of the McGrath gneiss and Warman quartz monzonite by Skillman (1945).

Winchell (1884) suggested and later revised (1888) a regional interpretation which included the central Minnesota intrusives in the Laurentian, supposed to extend from the North Shore of Lake Superior to the Minnesota Valley. Hall (1901) pointed out that the central Minnesota rocks intrude the Thomson formation, then believed to be Lower Huronian. Cheney (1915), assuming the Thomson formation to be Upper Huronian, placed the central Minnesota intrusives in the Keweenawan period. Schwartz (1942b) found evidence that the Thomson formation might be Knife Lake in age.

DESCRIPTIVE GEOLOGY

GENERAL REMARKS

Central Minnesota is remarkable for the diversity as well as the paucity of rock outcrops. Within the area included in this report are 3 sedimentary formations, 16 igneous rock types, and 4 metamorphic rocks.

The sedimentary rocks are the Benton clays and conglomerates (Cretaceous), the Hinckley sandstone (Upper Keweenawan), and the Fond du Lac arkose (Upper Keweenawan). These are all younger than the crystalline rocks of central Minnesota. The Benton occurs as small outliers and the Hinckley is known only in drill cuttings.

The igneous rocks range from norite to granite. The 16 rock types are of different composition and texture, but are not necessarily from different plutons; at least seven of these are facies or modifications of other types. The intrusives fall into four distinct groups: 1. the late dikes (Middle Keweenawan), 2. the Stearns magma series (Middle Keweenawan), 3. intrusives of intermediate composition (Late Algoman), and 4. basic intrusives (uncertain age).

The four metamorphic rocks include the Crow Wing formation (presumably Animikie), altered basic intrusives (probably Early Algoman), the McGrath gneiss (Early Algoman), and the Thomson formation (Knife Lake).

GEOLOGIC SUCCESSION IN CENTRAL MINNESOTA

Cenozoic
- Pleistocene
  - drift

Mesozoic
- Cretaceous
  - Benton formation

Proterozoic
- Keweenawan
  - Upper Keweenawan
    - Hinckley sandstone
    - Fond du Lac arkose
  - Middle Keweenawan
    - late dikes
      - granite porphyry

basalt
hypersthene melatrachybasalt porphyry
Stearns magma series
St. Cloud Red granite
Rockville quartz monzonite
porphyritic granite
quartz latite porphyry
Crystal Gray quartz monzonite
Keweenawan or Late Algoman
hornblende norite*
Animikie
Crow Wing formation*
Archeozoic
Algoman
Late Algoman
Freedhem tonalite
hornblende gabbro*
Warman quartz monzonite
Hillman gneissoid tonalite
St. Cloud Gray granodiorite
melagranodiorite
hornblende granodiorite
Early Algoman
actinolite gabbro*
McGrath gneiss
Knife Lake
Thomson formation

CRITERIA OF AGE RELATION

The age of the rocks relative to each other was determined by such evidence as the following:

1. A dike is younger than the rock it cuts.
2. An apophysis is younger than the rock it penetrates.
3. A roof-pendant is older than the rock which surrounds it.
4. An inclusion is older than the rock which encloses it.
5. A rock contaminated by xenocrysts is younger than the rock from which the xenocrysts came.
6. A rock dynamically metamorphosed is probably older than one not dynamically metamorphosed.
7. A rock cut by dikes, veins, or hydrothermal alteration is probably older than one not so cut.

All the intrusive rocks are older than the Fond du Lac formation of Upper Keweenawan age and younger than the Thomson formation of Knife Lake age; therefore, the entire sequence of igneous activity took place between Keweenawan and Knife Lake time. The Crow Wing formation can not be used to ascertain the age of the intrusives because its age is not positively known and there is no good evidence of its age relative to the central Minnesota intrusives.

The assignment of intrusive activity to both Algoman and Keweenawan periods is

*Proper position in the outline uncertain.

based upon the character of the accessory zircons. According to Tyler, Marsden, Grout, and Thiel (1940), in the Lake Superior region different varieties of zircon are characteristic of different periods of the Pre-Cambrian. A rock which contains accessory "normal" zircon is Keweenawan or younger; one which contains malacon and no "normal" zircon is Huronian; and one which contains "hyacinth" and neither malacon nor "normal" zircon is pre-Huronian. The late dikes and the Stearns magma series contain normal zircon; hence they are assigned to the Keweenawan period. The intrusives of intermediate composition and the McGrath gneiss contain hyacinth but neither malacon nor normal zircon, and they intruded the Thomson formation, supposedly of Knife Lake age; hence they are assigned to the Algoman period. This designation is well supported by field and petrographic evidence.

The Early Algoman intrusives have been metamorphosed; the Late Algoman intrusives show no evidence of metamorphism.

UPPER KEWEENAWAN

Fond du Lac Arkose.—The Fond du Lac formation (Stauffer and Thiel, 1941, p. 10) crops out in ledges at a few places along the Snake River between McGrath and Mora. It dips southward away from the area of crystalline rocks at 20° or less. Its contact with the crystalline rocks is not exposed but drill records show that it overlies a weathered igneous and metamorphic surface (Stauffer and Thiel, 1941, p. 13), some of which is unquestionably of the Stearns magma series. No dikes, no signs of metamorphism give any indication that the Fond du Lac arkose was intruded by the Stearns magma series or by a dike swarm; moreover, the abundance of feldspar suggests that the Stearns magma series may have contributed heavily to the Fond du Lac sediments. It seems probable that the swarm of felsite and basalt dikes in central Minnesota is contemporaneous with the felsite and basalt flows of eastern and northeastern Minnesota which lie beneath the Fond du Lac formation. It is concluded that the Fond du Lac formation is younger than all the intrusives of central Minnesota.

MIDDLE KEWEENAWAN

Late dikes.—Basalt and granite porphyry dikes are contemporaneous, contain normal zircon, and trend northeast toward the source of the Middle Keweenawan basalt and felsite flows in the Lake Superior syncline; therefore they are correlated with the flows.

Assimilation of schist in a basalt dike resulted in the formation of the rare rock, hypersthene melatrachybasalt porphyry.

GRANITE PORPHYRY: The granite porphyry occurs as dikes which average 15 feet wide although they range from less than a foot to 60 feet wide. Most dikes trend northeast, prevailingly N. 55° E. and N. 15° E. In approximately half the exposures, the granite porphyry dikes are adjacent to basalt or quartz latite porphyry dikes. The outcrops are scattered near St. Cloud, near Milaca, and along the Skunk and Platte rivers.

The granite porphyry is younger than all the other igneous rocks in central Minnesota except basalt. A basalt dike cuts and shows chilled borders against granite

porphyry along the West Branch of the Rum River in the SE¼ sec. 23, T. 38 N., R. 28 W.; on the other hand, a porphyry dike cuts basalt in the SW¼ SW¼ sec. 17, T. 38 N., R. 28 W. In composition and color the granite porphyry dikes are very similar to the St. Cloud Red granite, yet the chilled borders against the St. Cloud Red, the northeast strike parallel to the basalt dikes, and the contemporaneous intrusion with the basalt dikes indicate a much closer relation to the basalt than to the granite. All granite porphyry dikes are assumed to be closely related in time and origin because they have the same composition, the same minerals, the same texture, occur as dikes of the same general size and attitude, and show no discrepancies in age except with respect to basalt dikes.

The petrographic description is summarized as follows:

Color—pink to red.

Texture—porphyritic; feldspar phenocrysts dominant and about 10 mm. long, quartz and mafic phenocrysts 2–5 mm. long; groundmass granulitic or granophyric.

Phenocrysts—(in order of abundance) perthitic microcline, perthitic orthoclase, quartz, oligoclase, biotite, hornblende.

Groundmass minerals—quartz, orthoclase, hornblende, biotite, oligoclase-albite, microcline.

Accessory minerals—magnetite, normal zircon, apatite, sphene, pyrite, fluorite.

BASALT: Swarms of basalt dikes cut the St. Cloud Red, the Rockville, and the St. Cloud Gray intrusives in the vicinity of St. Cloud, where almost every quarry waste pile contains fragments of basalt, and as far southwestward as Rockville. Elsewhere dikes are less abundant. The width of the dikes ranges from a fraction of an inch to 12, or rarely 25, feet, the average being about 3 feet. The prevailing trend is N. 50°–65° E.

The petrographic description is summarized as follows:

Color—greenish black.

Texture—felsitic to fine diabasic; chilled borders almost glassy to felsitic.

Essential minerals—50 per cent augite in some sections or uralite in others, 40 per cent lath-shaped plagioclase zoned from calcic bytownite to oligoclase.

Accessory minerals—olivine, apatite, magnetite.

Chilled borders—a few small, sharply angular or needlelike phenocrysts of bytownite or labradorite; groundmass of glass, magnetite globulites, and minute plagioclase needles.

Approximately one fourth of the basalt dikes contain conspicuous xenocrysts of quartz and microcline, and less commonly of orthoclase, plagioclase, hornblende, biotite, or pyrite. The xenocrysts generally are rounded and partly corroded. They have a dusty alteration along the margin but not along fractures, grain boundaries, or the calcic cores of plagioclase grains. Many xenocrysts are surrounded by a ring of augite. They were derived largely from the Rockville or St. Cloud Red intrusives because the microcline is identical in color and development of perthite; the microcline grains, as in the St. Cloud Red and Rockville, are twice as large as the neighboring quartz grains; orthoclase, plagioclase, and hornblende are less common xenocrysts just as they are less common constituents of the St. Cloud Red and Rockville, yet when found they are identical to the corresponding minerals of these intrusives.

HYPERSTHENE MELATRACHYBASALT PORPHYRY: Along the west bank of the Mississippi River in the SE¼ sec. 23, T. 128 N., R. 29 W. are four small exposures of hypersthene melatrachybasalt porphyry. Less than a quarter of a mile upstream are outcrops of staurolite schist but contacts of the porphyry with the schist are not exposed.

The petrographic description is summarized as follows:

Color—dull dark gray.

Texture—porphyritic; 3 mm. phenocrysts of olivine and hypersthene, 1–2 mm. phenocrysts of hypersthene; groundmass 80 per cent of the rock, felsitic, poikilitic orthoclase and biotite crowded with small well-oriented euhedral hypersthene and labradorite.

Essential minerals—50 per cent reddish-brown magnesium-rich hypersthene, 20 per cent labradorite, 15 per cent orthoclase, 10 per cent olivine, 5 per cent iron-rich biotite.

Accessory minerals—apatite, magnetite.

By Johannsen's classification, this rock belongs to the group 3311H for which no name and no example are given. The term, melatrachybasalt porphyry, describes Johannsen's group 3311H and hence is applied to this dike rock.

The hypersthene melatrachybasalt porphyry is undoubtedly a schist-contaminated dike in the swarm of basalt dikes, for the unusual composition can be explained as the normal result of contamination of a basaltic magma by an aluminous sediment (Bowen, 1922, p. 543–550). Assimilation of a somewhat sandy biotite schist increases the proportion of alumina, iron, potash, and silica. As the schist dissolves, olivine precipitates and then reacts with the excess silica to form hypersthene, shown by a ring of radiating hypersthene crystals about olivine. Excess alumina and silica react with the augite that might form to precipitate magnesium-rich hypersthene and lime-rich plagioclase instead. The equal-sized hypersthene and labradorite crystals in the groundmass are probably the result of this reaction. The residual potash, alumina, iron, and silica cystallize last to form orthoclase and iron-rich biotite. The mutally embaying contacts of the orthoclase and biotite and their poikilitic structure support this interpretation.

Stearns magma series.—The most widespread facies of the Stearns magma series is the St. Cloud Red granite which locally contains augite-hornblende grains and assumes a deep red color. Prolonged deuteric reaction resulted in the porphyritic Rockville facies, and similar but later and more intense reactions produced the porphyritic granite facies. Quartz latite dikes appear to be early facies of the Stearns magma series contaminated by abundant xenocrysts from the St. Cloud Gray. A combination of contamination by St. Cloud Gray xenocrysts and deuteric reaction resulted in the Crystal Gray facies.

The "normal" zircons show that the Stearns magma series is Keweenawan; the cross-cutting basalt dikes suggest that it is earlier than the close of middle Keweenawan; and the similarity in color and composition to the granite porphyry dikes suggest that it is early Middle Keweenawan.

ST. CLOUD RED AUGITE-HORNBLENDE GRANITE: The St. Cloud Red granite crops out in western Mille Lacs County, in northeastern, central, and western Benton County, eastern and northwestern Stearns County, and central Morrison County

(Pl. I). It is quarried extensively near St. Cloud and marketed under several names, most commonly "St. Cloud Red."

One of the youngest rocks in central Minnesota it cuts and contains inclusions of the St. Cloud Gray granodiorite, the Freedhem tonalite, the Hillman tonalite, and the Thomson formation. The St. Cloud Red facies cuts an earlier facies of the Stearns magma series, the quartz latite porphyry; on the other hand, it seems to grade into the Rockville facies and the porphyritic granite facies.

The petrographic description is summarized as follows:

Color—pink to red; the local dark red of the granite at St. Cloud is probably due to oxidation of abundant hairlike epidote-pyrite veins.

Texture—medium granitoid; potash feldspar grains range from 0.5 to 1.5 cm. and are twice the size of the quartz; the mafites and plagioclase grains are smaller than the quartz grains.

Essential minerals—50 per cent pink perthitic orthoclase and microcline, 30 per cent gray quartz, 10 per cent white oligoclase, 10 per cent biotite.

Accessory minerals—hornblende, augite, hyacinth and normal zircon, apatite, fluorite, sphene, magnetite, albite.

The St. Cloud Red is an augite-hornblende granite because locally, especially near the St. Cloud Gray granodiorite, hornblende containing cores of augite is an essential mineral. As the St. Cloud Gray contains similar hornblende grains with augite cores, it seems very possible that those of the St. Cloud Red are xenocrysts.

Rockville Porphyritic Quartz Monzonite: Typical Rockville quartz monzonite crops out between St. Cloud and Richmond, but porphyritic quartz monzonite also crops out east of St. Cloud in T. 37 N., R. 31 W. and in sec. 17, T. 35 N., R. 30 W. The rock is quarried and sold under several trade names, but the most characteristic exposure is at Rockville.

The petrographic description is summarized as follows:

Color—typically pink, ranges to dark reddish gray.

Texture—granitoid, seriate; phenocrysts range from 1 to 6 cm. long and may show great variations in number and size over short distances; grains of the groundmass from 3 to 10 mm. long.

Essential minerals—35 per cent pink perthitic microcline and orthoclase, 30 per cent gray quartz, 25 per cent white andesine-oligoclase, 10 per cent biotite.

Accessory minerals—hornblende, hyacinth and normal zircon, apatite, sphene, fluorite, magnetite; allanite, pyrite, and calcite have been reported (Tatge, 1939, p. 305).

A flow structure, in some places conspicuous, in many places barely discernible, has a northeast trend and steep northwest dip. In general it becomes more obscure northeastward. The structure is best displayed by the orientation of the feldspar phenocrysts, but the mafites, the plagioclase of the groundmass, and some dark inclusions are similarly oriented.

The Rockville quartz monzonite and the St. Cloud Red granite are considered facies of a single intrusive for the following reasons: 1. There appears to be a complete gradation from the Rockville porphyritic texture to the St. Cloud Red granitoid texture; the feldspar grains are progressively smaller in the outcrops between Cold

Spring and St. Cloud. 2. Both rocks contain, in addition to pink perthitic microcline, large gray quartz grains which are about half the size of the microcline and are more conspicuous than the white plagioclase. 3. In both the St. Cloud Red and Rockville, the plagioclase is zoned from andesine to oligoclase with a very late albite phase. 4. Accessory normal and hyacinth zircon, apatite, and fluorite are common to both rocks. 5. No inclusion or dike of one in the other, and no other evidence that one intruded the other has been found.

Although the Rockville quartz monzonite has flow structure and the St. Cloud Red is massive, the structure grades northeastward from almost gneissoid to massive. Both rocks contain about 60 per cent feldspar but the Rockville quartz monzonite contains a greater proportion of plagioclase. It is possible that the St. Cloud Red granite contains a larger amount of plagioclase in the perthite, or it is possible that the proportion of potash feldspar in the Rockville was underestimated due to the large size of the phenocrysts.

The extremely coarse texture of the Rockville quartz monzonite is probably the result of deuteric action more prolonged than in other facies of the Stearns magma series.

PORPHYRITIC GRANITE: In sec. 35, T. 37 N., R. 31 W. are several outcrops of white porphyritic granite which are cut by abundant pegmatite dikes, aplite dikes, and quartz-epidote-chlorite-fluorite-pyrite veins. In the NE¼ sec. 35 a granite porphyry dike is chilled against the white porphyritic granite and white porphyritic granite is chilled against St. Cloud Gray granodiorite; in the SE¼ sec. 35, St. Cloud Red granite and white porphyritic granite appear to have a gradational contact. These field relations suggest that the white porphyritic granite is closely associated with the St. Cloud Red. The mineral composition and average texture are very similar to those of the Rockville facies of the Stearns magma series except that quartz is much more abundant.

The petrographic description is summarized as follows:

Color—white.

Texture—seriate granitoid to porphyritic; potash feldspar phenocrysts average 2 cm. but range from 0.5 to 8 cm.; groundmass ranges from coarse granitoid to felsitic.

Essential minerals—highly variable proportions of quartz, orthoclase, microcline, albite, andesine-oligoclase, biotite.

Accessory minerals—hornblende, normal zircon, apatite, muscovite, magnetite, pyrite.

Orthoclase and microcline are extensively replaced by albite as patch perthite (Andersen, 1928). Some quartz was formed by late deuteric reaction (by replacement); rows of blebs with simultaneous extinction run across several grains and corroded remnants of microcline perthite which extinguish simultaneously are isolated in patches of quartz. Large grains of quartz are embayed by microcline and fractures filled by microcline; hence some quartz must have crystallized before the microcline and a second, extremely corrosive generation of quartz subsequently attacked and replaced the microcline.

It seems probable that the white porphyritic granite is a facies of the Stearns

magma series which has been attacked and replaced by quartz- and albite-bearing solutions. The solutions, presumably, were associated with the pegmatite dikes and quartz-fluorite veins that cut the granite.

QUARTZ LATITE PORPHYRY: A dike of granophyre quartz latite porphyry in the NW¼ sec. 33, T. 124 N., R. 28 W. is about 300 feet wide and trends N. 65° E. A second dike in the SW¼ sec. 8, T. 124 N., R. 28 W. is 3 feet wide and trends N. 80° E. Quartz latite porphyry cuts St. Cloud Gray granodiorite but is cut by St. Cloud Red granite, basalt dikes, and granite porphyry dikes.

The petrographic description is summarized as follows:

Color—pinkish gray.

Texture—porphyritic; phenocrysts 2–8 mm. long, the larger ones in the center; groundmass felsitic, granophyre.

Phenocrysts—slightly less than half the rock; black uralite predominant at the border, bluish-gray oligoclase predominant in the center.

Groundmass—at the border 35 per cent orthoclase and microcline, 35 per cent quartz, 30 per cent hornblende; in the center 55 per cent orthoclase and microcline, 40 per cent quartz, 5 per cent hornblende.

Accessory minerals—biotite, magnetite-ilmenite, rutile, sphene, apatite, hyacinth and normal zircon.

The oligoclase phenocrysts are somewhat fractured; at a few places the fragments are displaced and the fractures filled with groundmass. Patch antiperthite shows a wide range of proportions of oligoclase to orthoclase. The presence of large grains of patch antiperthitic oligoclase and of uralite in a granophyre groundmass suggests that the grains are not primary phenocrysts but altered xenocrysts. The quartz latite dikes are probably early injections of St. Cloud Red granite which incorporated xenocrysts from the St. Cloud Gray at depth or plucked them from the walls in passing.

The distribution of phenocrysts, small at the border and large in the center, is commonly considered to be indicative of primary crystallization and negative evidence of xenocrysts. This is not necessarily true. Magma rising rapidly through a dike is retarded along the walls by friction. The turbulence thus created sweeps the magma and its xenocrysts against the wall and away again in eddy currents. As the magma cools adjacent to the walls, its viscosity there is increased; small xenocrysts are trapped but the larger ones may be carried away. Thus turbulence and increasing viscosity tend to separate xenocrysts in a dike on the basis of size. Shape, also, is a factor for particles more nearly spherical are less retarded by viscosity. In the quartz latite porphyry dikes, not only are the uralite xenocrysts generally smaller than the oligoclase, but they also have less sphericity; these two factors effectively separate the xenocrysts, uralite near the walls and oligoclase and quartz in the center.

CRYSTAL GRAY PORPHYRITIC QUARTZ MONZONITE: Crystal Gray quartz monzonite was observed only in the quarry in the NE¼ sec. 27, T. 124 N., R. 29 W.

This rock appears to be a facies of the Stearns magma series that was heavily contaminated by St. Cloud Gray and then attacked by deuteric reactions. In color and general appearance it bears a striking resemblance to the granophyre quartz latite dikes. Its composition and late deuteric reactions are similar to the Rockville

quartz monzonite, yet the gray plagioclase and abundant hyacinth zircon suggest contamination by the St. Cloud Gray granodiorite.

The petrographic description is summarized as follows:

Color—pinkish gray.

Texture—granitoid, seriate; phenocrysts 1–2 cm. long, grains of groundmass 1–5 mm. long.

Essential minerals—30 per cent orthoclase and microcline in 1–2 cm. pinkish-gray crystals and fine pink interstitial grains, 30 per cent greenish-gray andesine-oligoclase in 1 cm. crystals and fine interstitial grains, 30 per cent bluish opalescent quartz in grains 5 mm. and smaller, 10 per cent biotite in flakes 5 mm. and smaller.

Accessory minerals—albite, hornblende, apatite, hyacinth and normal zircon, magnetite.

Deuteric reaction is suggested by the following details: (1) most plagioclase contains orthoclase as patch antiperthite and quartz as wormy intergrowths, (2) microcline surrounds plagioclase and stringers of it cut both orthoclase and plagioclase, (3) late quartz embays feldspar grains and wormy intergrowths of quartz intersect grain boundaries of microcline, orthoclase, and plagioclase alike, and (4) albite is associated with quartz in intergrowths at grain boundaries.

MIDDLE KEWEENAWAN OR LATE ALGOMAN

Hornblende norite.—Norite crops out near the Sauk River in T. 123 N., R. 30 W. It is cut by dikes and apophyses of Rockville quartz monzonite and forms inclusions in the quartz monzonite. At the contact, the quartz monzonite is somewhat chilled and the norite is recrystallized. The norite is probably part of a large dike or sill; the grain size decreases in both directions from the center of the string of outcrops.

The petrographic description may be summarized as follows:

Color—black.

Texture—medium granitoid, ranges from 1 to 10 mm.

Essential minerals—35 per cent hornblende, 30 per cent hypersthene and augite, 30 per cent bytownite and labradorite, 5 per cent ilmenite.

Accessory minerals—magnetite, pyrite, chalcopyrite.

In the coarser facies the pyroxene is hypersthene and the plagioclase is bytownite whereas in the finer facies the pyroxene is hypersthene and augite and the plagioclase is labradorite.

LATE ALGOMAN

Summary.—The Late Algoman intermediate intrusives seem to be facies of a single magma series. They invade the same general region; they cut the Thomson formation and are cut by the Stearns magma series; they contain hyacinth but not normal zircon; they are not metamorphosed; and they have an intermediate composition with more than average proportion of quartz. But the detailed evidence is too weak to prove a single magma series.

The five major intermediate intrusives are the hornblende granodiorite, the St. Cloud Gray granodiorite, the Freedhem tonalite, the Hillman tonalite, and the Warman quartz monzonite. Minor intrusives are the hornblende gabbro and the

melagranodiorite which may be facies of the Freedhem tonalite and the St. Cloud Gray granodiorite respectively.

The hornblende granodiorite is unlike all the others in its oriented hornblende needles, its microscopic interstitial texture, and its assemblage of accessory minerals.

The St. Cloud Gray differ from the Hillman tonalite and the Warman quartz monzonite in texture, color, and mineralogy. The dark-gray facies of the St. Cloud Gray resembles the granodiorite facies of the Freedhem in texture, color, and composition; moreover they both contain rounded inclusions of an earlier border facies. On the other hand, the exposures are so distant and the typical facies so unlike that the identity of these two intrusives is uncertain.

The Freedhem tonalite is unlike the Hillman gneissoid tonalite in that it contains a larger proportion of hornblende and a more sodic plagioclase, and apparently was chilled at the borders with no *lit-par-lit* injection. The Freedhem tonalite is more basic and commonly coarser than the Warman quartz monzonite.

Some less foliated facies of the Hillman tonalite resemble the coarser facies of the Warman quartz monzonite in grain size, color, and composition, although the Hillman generally contains less acidic feldspar and more abundant quartz. The two seem to be different injections because exposures of massive Warman quartz monzonite lie in the line of strike within 3 miles of foliated Hillman tonalite.

Thus these five Late Algoman intrusives cannot be shown to be members of a single magma series. The age relations of these intrusives also are indeterminate because no contacts are exposed.

Freedhem hornblende tonalite.—The name Freedhem is applied to the hornblende tonalite because most of its outcrops are clustered about the town of Freedhem (Pl. I).

The appearance and composition of the tonalite vary greatly from one outcrop to another and even within a single outcrop. The darker, finer, and more basic rock is probably a border facies.

The petrographic description is summarized as follows:

Color—black to light gray.

Texture—fine to medium granitoid; weak primary foliation.

Composition—melatonalite to granodiorite, tonalite most common.

Essential minerals (of the most common facies)—40 per cent andesine-oligoclase, 35 per cent hornblende and biotite, 20 per cent quartz, 5 or less per cent orthoclase.

Accessory minerals—apatite, hyacinth zircon, sphene, magnetite, pyrite.

Hornblende gabbro.—Hornblende gabbro was quarried in the NE¼ sec. 13, T. 129 N., R. 30 W. and crops out in two places in the east bank of the Mississippi River at Little Falls. A dike of gabbro 12 feet wide, which cuts the Thomson formation at Little Falls, strikes N. 35° W. and dips 65° SW. At the quarry the gabbro is chilled against the hornblende granodiorite.

The petrographic description is summarized as follows:

Color—mottled green and white in sharp streaks which range from 10 to 95 per cent green.

Texture—medium granitoid; amphibole poikilitic with bytownite-labradorite inclusions; andesine-oligoclase interstitial to amphibole; quartz, orthoclase, and microcline interstitial to all and poikilitically enclose bytownite-labradorite; chilled borders prophyritic to diabasic.

Essential minerals—proportions but not microscopic characteristics vary from streak to streak; 75 to less than 5 per cent amphibole, 20 to 60 per cent plagioclase; 5 to 10 per cent biotite, 5 to 40 per cent quartz, orthoclase, and microcline.

Accessory minerals—augite, apatite, sphene, magnetite-ilmenite, hyacinth zircon.

The amphibole is zoned from pale yellow-green hornblende in the center to blue-green amphibole at the edge. Some grains contain augite cores. The bytownite-labradorite laths are intensely altered and corroded whereas the andesine-oligoclase grains are fresh-looking.

The first generation of this rock seems to have been a diabase of augite-hornblende and bytownite-labradorite as shown by the composition and texture of the borders and the remnants poikilitically enclosed in later minerals. The gabbro appears to have been a diabase that was partly strewed and largely replaced in streaks by later, more silicic and alkalic fluids.

The quarry rock was probably not a dike, because the outcrops are too scattered. It may have been a small pluton or, more probably, the border facies of a large pluton. Although the late solutions may well have come from the Stearns magma series, the diabasic border and hyacinth zircon suggest a closer affinity to the Freedhem tonalite.

Warman quartz monzonite.—Warman quartz monzonite is exposed along the Snake River in T. 42 N. and T. 43 N., in the vicinity of the Ann River, and in quarries at Warman, Isle, and Pierz. It is cut by basalt dikes and contains inclusions and roof pendants of the Thomson formation. A dike of Warman quartz monzonite is reported to cut the McGrath gneiss (Harder and Johnston, 1918, p. 45–46).

The petrographic description is summarized as follows:

Color—white to very light gray; may be weathered to pink, red, or yellow.

Texture—medium granitoid with poikilitic orthoclase phenocrysts 1–3 cm. long; massive except locally where there is a slight primary foliation.

Essential minerals—30 per cent white oligoclase-albite, 30 per cent white orthoclase, 25–30 per cent grayish-yellow quartz, 5–10 per cent biotite.

Accessory minerals—apatite, hyacinth zircon, sphene, rutile, magnetite, ilmenite, microcline, muscovite, hornblende, augite.

Hillman gneissoid biotite tonalite.—The Hillman gneissoid tonalite crops out along Hillman Creek (whence the name), in the vicinity of the Skunk and Little Skunk rivers, and near the Rum River (Pl. I).

Inclusions and schlieren of the Thomson formation are common, locally making more than half the rock surface. Foliation, strongest where inclusions are most abundant, trends northeast with steep dips except near the Rum River where it trends north.

The petrographic description is summarized as follows:

Color—gray.

Texture—foliated medium granitoid, locally seriate; foliation in part primary, mostly from *lit-par-lit* injection of schist.

Essential minerals—45 per cent white andesine, 40 per cent white quartz, 10 per cent biotite, 5 per cent hornblende.

Accessory minerals—orthoclase, magnetite, hyacinth zircon, apatite, sphene, augite, garnet.

St. Cloud Gray augite-hornblende granodiorite.—The trade name, St. Cloud Gray, is applied here to the gray granodiorite and its derivatives which lie within 10 miles of St. Cloud (Pl. I).

Small round inclusions are abundant and scattered throughout the rock. Some can be identified as Thomson formation and some as the melagranodiorite border facies of St. Cloud Gray. Basalt and granite porphyry dikes are common in the St. Cloud Gray. Dikes and apophyses of the St. Cloud Red twist and branch irregularly and in some places form a network in the St. Cloud Gray. Aplites and pegmatites, largely from the St. Cloud Red, are abundant.

Although massive, the St. Cloud Gray is far from homogeneous. Every exposure is dotted with small dark inclusions and schlieren, cut by numerous dikes and veins and irregularly altered to a lighter, pinker rock. This pink facies appears to be granodiorite that was granitized by St. Cloud Red. The evidence is as follows: 1. All gradations between dark-gray granodiorite and light-pink granite can be found. Even where the St. Cloud Gray is pink, it contains dark knots of the same size and distribution as those in the unaltered St. Cloud Gray; the St. Cloud Red does not contain such knots. 2. The pink alteration may be in streaks, stringers, and elongate patches, or in zones as wide as 1500 feet and as deep as 100 feet. 3. The alteration is stronger and more extensive nearer exposures of St. Cloud Red; it is especially intense at the tips of pegmatite dikes which can be traced to the St. Cloud Red and adjacent to these dikes. Nevertheless, some pegmatites cut St. Cloud Gray granodiorite which is only slightly altered. 4. The altered zones bear no relation to the surface; the alteration is found at the bottom of the deepest quarries and may be absent at the top. 5. The altered zones are not related to veins; adjacent to veins is a red or white hydrothermal alteration very different from the pink alteration. 6. Xenoliths of St. Cloud Gray in St. Cloud Red show all degrees of alteration from gray granodiorite to pink granite, indeed, some are reduced to a mere shadow. 7. Xenoliths of St. Cloud Gray are angular and have sharp contacts even if intensely altered. 8. Replacement is shown by such microscopic evidence (Krum, 1935) as plagioclase replaced by microcline and albite as patch antiperthite, poikilitic orthoclase, patch and chessboard perthite in orthoclase, microcline replaced by quartz-plagioclase myrmekite, and embayments and stringers of quartz.

The St. Cloud Gray is not an early facies of the St. Cloud Red because some dikes of St. Cloud Red are chilled against the St. Cloud Gray, inclusions of St. Cloud Gray are angular, all contacts are sharp, and the St. Cloud Red contains normal zircon whereas the St. Cloud Gray contains only the hyacinth type.

The petrographic description of the dark-gray (least altered) St. Cloud Gray is summarized as follows:

Texture—medium granitoid.

Essential minerals—50 per cent light-gray andesine-oligoclase, 15 per cent augite and hornblende, 15 per cent gray (or locally blue) quartz, 10 per cent white orthoclase, 10 per cent biotite.

Accessory minerals—hyacinth zircon, apatite, sphene, ilmenite, magnetite; and pyrite and chalcopyrite (Krum, 1935, p. 16).

The petrographic description of the light-pink (most altered) St. Cloud Gray is summarized as follows:

Texture—medium to fine granitoid.

Essential minerals—25 per cent pink orthoclase, 25 per cent pink microcline, 25 per cent gray quartz, 20 per cent light-gray andesine-oligoclase, 5 per cent augite, hornblende, and mostly biotite.

Melagranodiorite.—Melagranodiorite crops out in the vicinity of St. Cloud, chiefly east of the Mississippi River southwest of Watab (Pl. I). It is cut by dikes and stringers and forms inclusions in the St. Cloud Red. Dikes of granite porphyry and basalt cut the melagranodiorite. The St. Cloud Gray contains small knots of melagranodiorite but no dikes of one cutting the other are known. The "Gray" dikes reported in the literature are St. Cloud Red granite which contains strewed, rounded, and altered plagioclase laths and augite-hornblende grains.

The melagranodiorite is believed to be an early facies of the St. Cloud Gray granodiorite because: (1) Both are older than the St. Cloud Red. (2) Although they crop out near each other, no dikes of one cut the other. (3) Inclusions of melagranodiorite in St. Cloud Gray are all very small and rounded as would be expected were the melagranodiorite a border facies of the St. Cloud Gray. (4) The gradation in texture and mineralogy is that expected from the central mass to the border facies—the proportion of mafites is slightly greater, the plagioclase is slightly more calcic, the proportion of quartz and orthoclase is slightly less, and the texture is slightly finer.

The petrographic description is summarized as follows:

Color—dark gray.

Texture—medium granitoid, somewhat diabasic.

Essential minerals—40 per cent augite and hornblende, 35 per cent plagioclase zoned from labradorite to oligoclase, 10 per cent biotite and chlorite, 10 per cent orthoclase, 5 per cent quartz.

Accessory minerals—magnetite, sphene, hyacinth zircon, apatite.

The melagranodiorite, like the St. Cloud Gray, contains rounded inclusions of a similar but finer-grained, more basic rock. This is believed to be a still earlier facies of the St. Cloud Gray. The petrographic description is summarized as follows:

Color—black.

Texture—fine granitoid, somewhat diabasic.

Essential minerals—60 per cent augite and hornblende, 25 per cent plagioclase zoned from labradorite to oligoclase, 10 per cent biotite, 5 per cent orthoclase and quartz.

Hornblende granodiorite.—A few small patches of hornblende granodiorite are exposed in the gabbro quarry in the NE¼ sec. 13, T. 129 N., R. 30 W. It is in contact with the gabbro, which here grades into a fine-grained porphyritic rock whereas the hornblende granodiorite shows no change in texture. The lineated hornblende needles of the granodiorite suggest a relationship to the lineated hornblende-epidote granite of Cass and Todd Counties which is said to resemble the Giants Range granite (Harder and Johnston, 1918, pp. 30–32).

The petrographic description is summarized as follows:

Color—streaked white and black.

Texture—granitoid, modified by a beadwork of fine-grained feldspar, quartz, and apatite along grain boundaries; hornblende needles in parallel alignment.

Essential minerals—65 per cent andesine-oligoclase, 10 per cent hornblende, 10 per cent biotite, 10 per cent quartz, 5 per cent orthoclase and microcline.
Accessory minerals—apatite, hyacinth zircon, rutile, augite, sodic amphibole.

EARLY ALGOMAN

Actinolite gabbro.—Actinolite gabbro crops out in secs. 3 and 9, T. 39 N., R. 24 W. The exposures are riddled with veins of quartz, pyrite, ilmenite, and calcite.

The actinolite gabbro is older than the Warman quartz monzonite, which crops out 3 miles to the north; the Warman quartz monzonite contains no similar veins, shows no evidence of metamorphism, and near the actinolite gabbro and not elsewhere, it contains abundant ilmenite and sphene that doubtless were derived from the actinolite gabbro.

The petrographic description is summarized as follows:
Color—mottled green and white.
Texture—medium granitoid, almost diabasic; now feathery due to development of actinolite.
Essential minerals—35 per cent labradorite, 25 per cent actinolite, 20 per cent zoisite, 10 per cent chlorite and sericite, 5 per cent introduced pyrite, ilmenite, calcite, and quartz.

The original composition of the rock appears to have been 60 per cent labradorite and 40 per cent pyroxene, olivine, and ilmenite.

McGrath kaligranite augen gneiss.—The largest exposures of augen gneiss are 2 miles southwest of McGrath. Other exposures are near Dads Corner, Arthyde, and Denham.

The McGrath gneiss penetrated the Thomson formation *lit-par-lit*. The foliation of the gneiss is exactly parallel to and merges with that of the Thomson formation, alternating biotite-rich and hornblende-rich bands in the gneiss duplicate the alternating layers of biotite-rich and hornblende-rich schist; all gradations can be traced from biotite-rich bands to schlieren and inclusions of Thomson formation in the gneiss.

Following its *lit-par-lit* injection into the Thomson formation, the McGrath gneiss has been dynamically metamorphosed, as shown by the feldspars which are fractured, have mortar structure, augen structure, and granulated structure. Quartz has the sutured structure characteristic of recrystallization. The McGrath gneiss is placed in Early Algoman; Late Algoman intrusives in this district seem to be unmetamorphosed.

The petrographic description may be summarized as follows:
Color—pink and black bands.
Texture—medium-grained, foliated, granulated.
Essential minerals—30 per cent quartz, 25 per cent orthoclase, 25 per cent pink microcline, 10 per cent biotite, 5 per cent muscovite, 5 per cent albite.
Accessory minerals—hyacinth zircon, sphene, apatite, ilmenite, hornblende, sericite, rutile, garnet.

KNIFE LAKE

Thomson formation.—The Thomson formation crops out extensively between Denham and Duluth. Near Cloquet and Carlton the formation is interbedded slate and graywacke which grades to garnetiferous biotite schist at Denham (Schwartz, 1942b, p. 1009). The Thomson formation crops out along the Mississippi River at Little Falls, where it is a phyllite, and 9 miles south of Little Falls, where it is stuarolite-biotite schist.

Locally the Thomson formation contains facies of hornblende schist, muscovite schist, chlorite schist, and dolomite. Calcareous concretions (Schwartz, 1942a) and abundant quartz veins distinguish the Thomson formation and serve to identify inclusions and roof pendants.

CONCLUSION

The area of central Minnesota, previously mapped as "undifferentiated Pre-Cambrian," contains a country rock of schist which has been invaded by three intrusives of batholithic dimensions (Pl. I). During Early Algoman time, the Thomson formation was metamorphosed to schist and injected *lit-par-lit* by the McGrath granite gneiss. Dynamic metamorphism granulated this injection gneiss to an augen gneiss. Later in the Algoman period, the region was invaded by magma of intermediate composition which apparently took the form of four or five related but separate injections. In the Middle Keweenawan the region was invaded for a third time, this time by the granitic Stearns magma series.

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COLORADO
NEW MEXICO

104°

T 32 N

T 31 N

T 30 N

T 29 N

BARTLETT MESA

HORSE MESA

Sugarite

RATON

Creek

GRANT

MAXWELL

Dillon

Chicorica Creek

Raton Creek

HUNTER MESA

JOHNSON MESA

TOWNDROW PEAK

RED MT.

Trinchera Pass

Emory Gap

Oak Canyon

Cimarron

Seco

EMORY PEAK

HEREFORD PARK

COLFAX COUNTY

UNION COUNTY

Folsom

RED RIVER PEAK

Clifton House

BLACK MESA

OR

Creek

MELOCHE MESA

CAPULIN MOUNTAIN

Des Moines

Capulin

(abandoned)

Santa Fe Forks

Gallo Creek

Una de Gato Creek

MIRANDA

ROUND MESA

GREEN MOUNTAIN

Blosser Creek

Hebron Reservoir

BLOSSER MESA

MESA LLARGO

HORSESHOE CRATER

SIERRA GRANDE

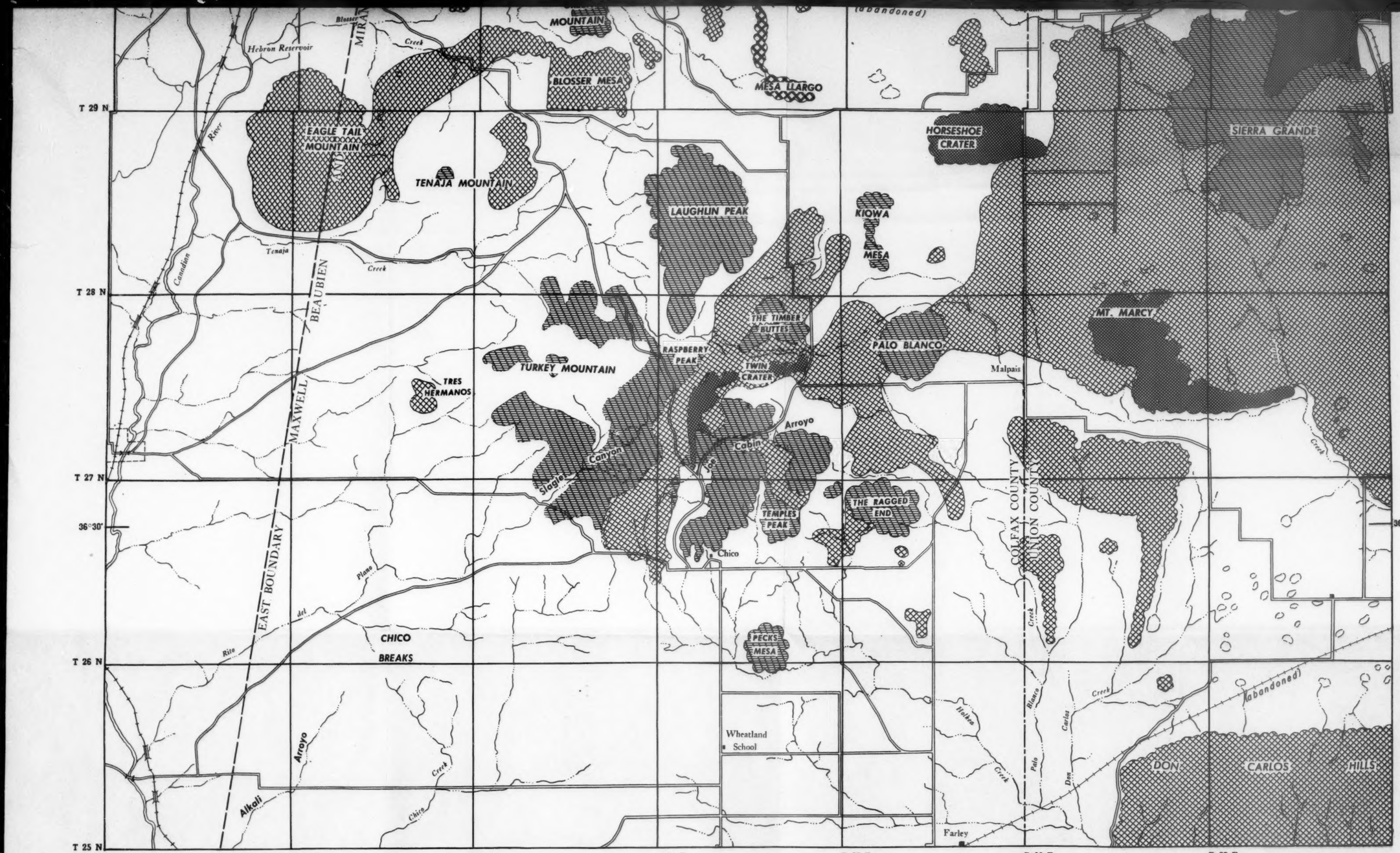
EAGLE TAIL MOUNTAIN

Canadian River

TENAJA MOUNTAIN

LAUGHLIN PEAK

KIOWA



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Geological Society of America 1949

AREAL IGNEOUS GEOLOGY

Volcanic rocks in parts of Colfax and Union counties, New Mexico

0 5 10 15 Miles

QUATERNARY VOLCANICS

High-level basalts, capping higher mesas	Qbr	RATON BASALT
Intermediate basalts, on lower mesas, sometimes on general surface level	Qbl	CLAYTON BASALT
Recent basalt, on newer cones and as tongues in river valleys	Qbr	CAPULIN BASALT
Non-basaltic igneous rocks, mostly surface flows, some stocks and dikes.	Qc	CHICO PHONOLITE, RED MT. DACITE SLAGLE TRACHYTE

LEGEND

City Boundary

Roads

Railroads

Intermittent Streams

Towns

Playa Lakes

Formation Boundary Exposed

Formation Boundary Hidden

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VOLCANIC ROCKS OF NORTHEASTERN NEW MEXICO

BY ROBERT F. COLLINS

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ABSTRACT

Eastern Colfax County and northern Union County in northeastern New Mexico contain over 700 square miles of basalt flows which were fissure eruptions chiefly, although extrusion loci are as yet not correlated with post-Eocene regional structure. Physiography indicates three periods of basalt extrusion, separated by active stream erosion. Scoria cones are present on flows of all periods but are most numerous on the intermediate Clayton flows. Lithologic character correlates with the age of extrusion. Olivine basalts predominate in all three periods. Clayton basalts vary most in mineralogy and include olivine basalts, olivine-free basalts, olivine basalts with quartz inclusions, feldspathoid basalts, and basanites. Recent Capulin basalts have the least olivine and the best-developed plagioclase microphenocrysts. Dacites, andesites, soda-trachytes, and phonolites are slightly older than Clayton basalts and definitely younger than the Raton basalts. The dacites are relatively uniform and form steep, eroded cones in eastern Colfax County. Soda-trachytes are rarest and closely bunched in central eastern Colfax County. Phonolites are found in central eastern Colfax County as flows, sills, and dikes. All the Quaternary igneous rocks of the area have probably originated from one magma whose original composition approximated an olivine basalt.

INTRODUCTION AND ACKNOWLEDGMENTS

The northeastern corner of New Mexico is an area of 4271 square miles whose geology has not been systematically described before. Its rugged surface of Cretaceous sediments and Quaternary lava flows is arid, thinly settled, and difficult of access. Except for the Raton coal field in the northwest corner, it has no mineral industry. The late S. P. Baldwin studied the field geology in 1893 and 1894, his work was continued and considerably amplified by the writer, with Baldwin's material assistance and encouragement, in 1926, 1927, and 1935; in 1940 and 1948 the writer's colleague, Helen R. Stobbe, did field work in eastern Colfax County.

Geologic literature says little about the area. St. John (1876, p. 283, 305–308), Stevenson (1881, p. 281), Hill (1891, p. 99), and Lee (1912, p. 357–365) referred briefly to the igneous geology of the region, mostly in its western part. Harley (1940, p. 27) and Garrett (1920, p. 78) refer to it. Darton (1921, p. 189–194, 1928, p. 64–65, 296–318) described the stratigraphy of Dry Cimarron canyon, Lee (1917, 1924), and Lee and Mertie (1922, p. 1–17) supplied much reference material for the Raton-Brilliant-Koehler portion of the area.

The present paper and its companion petrological paper by Stobbe (1949) offer the first systematic description of the igneous geology of this large section of northeastern New Mexico. It has not been possible to write more than a reconnaissance article; the field is too large and the facilities too limited.

The writer wishes to express his sincere appreciation to the many who have helped during the preparation of this report, especially to his old friend, Mark C. Bandy.

His colleagues Helen R. Stobbe, Benjamin M. Shaub, and Howard A. Meyerhoff have given generously of their time and effort. Charles P. Berkey has been the writer's long-time guide and inspiration. Mr. and Mrs. E. Roe Seward of Chico have aided greatly through their warm hospitality. Miss Anne Selden has drawn the geologic map and Miss Josephine Wasko has been patient, kind, and indispensable as secretary.

REGIONAL GEOLOGY

The area described in this paper extends 50 miles southward from the Colorado line and 86 miles westward from the Texas-Oklahoma line, is rectangular, and includes the northern part of Union County and the eastern part of Colfax County. It is part of the highly dissected western edge of the Great Plains, and includes the New Mexican portion of the Raton section.

The regional structure includes a broad syncline in the western part and a broad anticline in the central part. Both strike about 12 degrees east of north, involve sedimentary rocks from Triassic through Eocene, and are beveled by a post-Eocene erosion surface on which the extrusives rest. The eastern half of the area has a gentle southeastern regional dip that continues into the Texas panhandle.

The exposed sediments are largely Upper Cretaceous shales, limestones, and sands, with continental Eocene preserved in the western syncline, and Jurassic and Triassic continental clastics exposed in the Dry Cimarron canyon along the Colorado boundary (Table 1). In the southern portion, unconsolidated Ogallala sands overlie the Cretaceous unconformably. The stratigraphy is described by the author in a subsequent paper; although there is evidence of older surface rocks than the Dockum, the formations named in Table 1 are the dominant surface sediments.

Physiographically, the area is a trenched plateau. The mesas are capped with basalt, except in the northeast quarter where Dakota sandstone covers the stream divides. Phonolite flows are prominent in the southwest near Chico. Volcanic cones of all sizes abound; from some, long tongues of basalt have flowed down present stream valleys. Surface features are dominated by the lava mesas and the larger cones. Raton Mesa, Hunter, Bartlett, Johnson, and Meloche mesas, Eagle Tail Mesa, Mesa Llargo, the Folsom-Clayton Mesa, and Don Carlos Hills are the larger tables. Sierra Grande, the largest cone, has an elevation of 8739 feet and a basal diameter of over 8 miles. Laughlin Peak, Palo Blanco, Eagle Tail Mtn., Mt. Capulin, Turkey Mtn., Mt. Dora, Rabbit Ear Mtn., Mt. Clayton, Robinson Mtn., Burnt Mtn., Emory Peak, and Devoy Peak are other large and well-marked cones; scores of others are unnamed.

Mt. Capulin, a National Monument 6 miles south of Folsom, is an extremely well-preserved basaltic cinder cone and one of the youngest cones in the area. Several of the youngest lava flows spread from it. Approximately 10 miles northwest of Capulin and west of the town of Folsom is the type locality for the Folsom culture. Here in the Hereford Park country in 1926, the famous Folsom points were found associated in place with extinct *Bison taylori* remains.

The geologic history (Baldwin and Collins, 1928, p. 161) of the area is summarized as follows: local and marked folding of the Dockum and older beds at the end of the

TABLE 1.—*Sedimentary rock table, Northeastern New Mexico*

Quaternary		Unconsolidated gravels	Thickness (feet)	
Tertiary	Pliocene	Ogallala formation	0–150	Yellow sand, some weak lime cement
	Eocene	Raton formation	1150	Buff sandstone, brown shale, and coal seams
Upper Cretaceous	Montanan	Vermejo formation	0–200	Dark-brown to drab shale and buff sandstone, coal seams
		Trinidad sandstone	100	Massive, light-gray, medium-grained sandstone
		Pierre shale	1800	Olive-gray shale, some limestone at top, and sand near bottom
	Niobrara	Apishapa shale	300	Limy shale, gray to tan. Some sandy layers
		Timpas limestone	50	Gray, impure, soft shaly limestone
	Benton	Carlile shale	150	Dark-gray limy shale
		Greenhorn limestone	50–80	Gray limestone and shale interbedded
		Graneros shale	150	Dark-gray shale
	Dakotan	Dakota sandstone	100	Tan to buff medium-grained sandstone, massive and crossbedded
Lower Cretaceous		Purgatoire formation	150	Gray to buff massive sandstone overlain by thin dark shale
Jurassic		Morrison formation	150–300	Maroon to gray-green shales and sandstones interbedded, buff to brown sandstone
		Exeter sandstone	0–90	White sugary aeolian sandstone poorly cemented, massive crossbedded, and lenticular
Triassic		Dockum group	500+	Red sandstone and shale; local white limestone lenses, some gray sand

Triassic, erosional break ending with deposition of Jurassic Exeter sand followed by deposition of 3700 feet of continental and marine clastics through Upper Cretaceous, development of a slight unconformity at end of Cretaceous, deposition of Eocene coal measures, broad folding and warping in the Tertiary followed by erosion to a

TABLE 2.—*Extrusive igneous rocks of northeastern New Mexico*

Map symbol	Formation	Lithology	Chemical description (after Stobbe)	Localities
Qbr	Capulin basalts	Black, dense to vesicular and scoriaceous; large feldspar phenocrysts, small olivines common, groundmass has glass. Some pyroclastics.	Undersaturated with respect to silica in the dark minerals. Sub-aluminous.	Capulin Mtn. and flows, northeast flank of Sierra Grande flow, Horseshoe Crater, Mt. Marcy, south cone of Twin Crater.
Qbi	Clayton basalts	Gray to black, vesicular, amygdaloidal and scoriaceous; small olivine phenocrysts common, some olivine-free and feldspathoid basalts. Rarely diabasic.	Undersaturated with respect to silica in the dark minerals. Sub-aluminous. In feldspathoid basalts alkalies also unsaturated with respect to silica.	Yankee Volcano, Hunter Mesa, Meloche Mesa, Black Mesa (Colfax Co.), mesa east of Meloche Mesa, Blosser Mesa and Gap, Eagle Tail Mtn. and Mesa, Twin Crater, Temple Peak area, Joe Cabin Arroyo, Folsom-Clayton Mesa, on Sierra Grande, Hereford Park, Robinson Mtn., Burnt Mtn., Emory Peak, Briggs Canyon.
Qa	Chico phonolites	Green, aphanitic, dense; large feldspar phenocrysts, some pyroxene needles. Heavily jointed.	Unsaturated with respect to silica, alkalies partly or wholly unsaturated. Peralkaline, with alumina less than alkalies.	Laughlin Peak flows, Kiowa Mesa, Chico, Temples Peak, The Ragged End, Pecks Mesa, Red Hill, Turkey Mtn., Slagle Canyon, Joe Cabin Arroyo, Timber Buttes, Chico Breaks.
Qa	Slagle trachytes	Light-tan, fine-grained; chalky feldspar phenocrysts, hornblende needles. Flow structure evident.	Oversaturated with respect to silica, some excess alumina to enter dark minerals.	Joe Cabin Arroyo, Red Hill, Turkey Mtn., Slagle Canyon.
Qa	Red Mountain dacites	Light-gray, groundmass aphanitic with needles of hornblende, some feldspar phenocrysts. Pink on weathering. Strong flow structure.	Some sub-aluminous with little excess alumina to enter dark minerals. Some peralkaline with alumina less than alkalies.	Towndrow Peak, Red Mtn., Cunningham Butte, Green Mtn., Palo Blanco, Laughlin Peak, Raspberry Peak, Sierra Grande, Meloche Mesa, Turkey Mtn.

TABLE 2.—*Continued*

Map symbol	Formation	Lithology	Chemical description (after Stobbe)	Localities
Qbe	Raton basalts	Medium- to dark-gray, fine-grained, vesicular; small olivine phenocrysts. Rarely diabasic. Some iddingsite.	Undersaturated with respect to silica in the dark minerals. Subaluminous.	Johnson Mesa, gap between Hunter and Johnson Mesas, Mesa Llargo, Hereford Park, Oak Canyon, Devoy Peak, mesa north of Valley P.O., Black Mesa (northeast Union Co.)

plane of low relief and regional tilting down to the southeast. During and shortly after the tilting, the oldest Pleistocene basalt sheets were extruded, followed by extrusion and intrusion of dacites and alkaline rocks, in turn followed by two more periods of basalt extrusion, the last of which was probably Recent.

ROCK CLASSIFICATION

The classification of the igneous rocks in northeastern New Mexico is based on the work of Lee and Mertie (1922), on the author's field studies, 1926–1935, and on the petrologic paper by Professor Helen R. Stobbe (1949). Miss Stobbe has worked with the writer since 1937 and has had free access to his field specimens, thin sections, and maps. The microscopic determinations and rock classifications she publishes are in agreement with the writer's field studies. Stobbe says (1949, p. 1048).

"the classification is a mineralogical one . . . based upon the presence or absence of critical minerals such as quartz, olivine, and nepheline which represent either over-saturation or under-saturation of the magma with respect to silica; because these minerals indicate conditions in the cooling history and genesis of the magma . . . . These rocks can be further subdivided according to the kind of dark mineral present which indicates whether there is an excess or deficiency of alumina present."

Stobbe's classification, together with working field equivalents, are given in Table 2. Detailed study in field and laboratory, with the aid of adequate large scale maps will undoubtedly modify the classification and map boundaries, meanwhile the grouping given here is of value.

The high-level olivine basalts are named the *Raton basalts* in this paper after Raton Mesa. The Raton basalts are here understood to include Lee and Mertie's two oldest basalts which they designate Qb^1 and Qb^2. (Lee and Mertie, 1922, p. 9).

The hornblende dacites of the area are here designated as the *Red Mountain dacites* after a large eroded cone composed of these rocks, located on the eastern half of Johnson Mesa.

The rarer trachytes found in the southwest are named the *Slagle trachytes* from Slagle Canyon, west of Chico, T. 26 N., R. 25 E., where they are well exposed in the canyon walls.

The extensive flows of phonolite are named the *Chico phonolites* after the excellent exposures of this rock in the township of Chico.

The large group of intermediate basalts are named the *Clayton basalts* after the outcrops on the large Folsom-Clayton Mesa near Clayton, New Mexico. This group is younger than the Raton basalts, Red Mountain dacites, Slagle trachytes, and Chico phonolites. It is equivalent in age to Lee and Mertie's basalts designated as Qb^3.

The youngest basalt group, probably Recent, is named the *Capulin basalts* after the cone and flows of Mt. Capulin which are typical of the lavas of this most recent period of eruption.

BASALTIC ROCKS

AREAL GEOLOGY

Field characteristics.—The basaltic lava flows of the southern part of the eastern Rocky Mountain front, which extend from Trinidad, Colorado, to Las Vegas, New Mexico, and are widely known from their arresting exposures in and around Raton Pass, ramify widely eastward over Colfax and Union Counties, New Mexico, and are a major feature of the geology of the northeastern portion of that state. Over 700 square miles in these two counties are now covered by basalt surface flows, divided into three morphologic groups: the mesas, the cones, and the long flows.

The mesas, whose boundaries are irregular and whose area and relief vary within wide limits, include the Folsom-Clayton Mesa of Union County extending for 52 miles from Folsom to Clayton, with an area of over 400 square miles; Johnson, Bartlett, Horse, Eagle Tail, and Raton mesas in the Trinidad-Raton district; the Don Carlos Hills platform which covers 65 square miles, and the well-known Mesa de Maya north of Union County, in Colorado. Scores of smaller tables, ranging down to buttes, are plentiful over most of the area (Pl. 2). The surface of the basalt mesas is covered thinly with residual soil in most places, and on the lower mesas variable amounts of Quaternary loess has been added to the decomposition products. Many of the smaller mesas, and a few localities on the larger mesas, lack an effective soil cover and scoriaceous and ropy lava surfaces appear through the grass roots. Nevertheless the mesa surfaces are flat or very gently undulating. Small, shallow, circular basins are plentiful south of Des Moines and Grenville in Union County and, although they are covered with loess and soil, indicate lava-crust collapse caused by outflow of liquid lava from the center of the flow. Except on Johnson Mesa, the soil cover is seldom thick enough to permit extensive cultivation, and the land use is limited to grazing.

Scoriaceous basaltic cones are very numerous in the basaltic areas; there are several hundred if the smaller cones are included. Mt. Capulin, the most perfect and one of the larger examples of the cinder cones in the 48 states, is a beautifully symmetrical, rounded cone 1½ miles in diameter and 1500 feet high above its base and possesses a well-preserved crater with rim intact. Its sides are composed of beds of basaltic ash, lapilli, and small bombs, usually well sorted and stratified, which slope at the angle of repose and are interbedded with thin layers of caliche. Numerous other

cones of the same type and approximate size include Eagle Tail Mountain, Horseshoe Crater, Burnt Mountain, Emory Peak, Devoy Peak, Mt. Marcy, Mt. Clayton, Mt. Dora, and Rabbit Ear Mountain, whose craters are more or less breached in the southwestern quadrant. A second, low-angle or shield type cone is known also, although examples are far less numerous. The shield volcanoes merge with the mesa surface and seldom exhibit any accumulation of lapilli except very locally around the vent. Distinct craters are lacking, but broad flows of basaltic rock with a ropy and scoriaceous upper surface can be traced from the center of the cone itself. Excellent examples of the low-angle type are Round Mesa, Blosser Mesa, Yankee Volcano, and the mesa surface southwest of Burnt Mountain, all in eastern Colfax County.

The long, tongue-like flows, found in present-day valleys (Pl. 2), have issued from cones rather than fissures and are distinctly linear in their proportions because the lava was confined by the local stream topography at the time of extrusion. The surface of the tongue is always rough, ropy, and irregular, and the flows exhibit abundant evidence of flow-unit phenomena (Nichols, 1936, p. 617–630).

The morphological subdivision of the basaltic rock masses does not imply any genetic significance to the categories. There are genetic groups, but the surface shape of the basalts was determined largely by contemporaneous topography. The broad sheets, which now form the caprock of mesas, are believed to have flowed over broad basin-like depressions. This is suggested in some of the larger mesas, particularly Johnson Mesa, by a slight concavity of the upper surface together with some low scoria cones near the rim. However, in the vicinity of Clayton in eastern Union County, the southern Don Carlos Hills, the area south of Lake Wetherby in central northern Union County, and in the mesa forms between Johnson Mesa and Emory Gap, the areal pattern of the basalt strongly indicates that the original lava extensions flowed down confining valleys and yielded tongue-like forms. Although a large amount of post-extrusive erosion appears to have occurred, the fact that very few basalt pebbles are found beyond the limits of present talus leads to the belief that there has been relatively little erosion of the main basalt masses, and that the present extent of the basalt sheets and tongues approximates the original extent of the flows.

Age relationships.—The extrusive rocks, including the basalts of northeastern New Mexico, have been assigned to the Quarternary by Lee and Mertie (1922, p. 8, 13) and Darton (1905, p. 178–179). The basalts of Bartlett, Johnson, Raton, and Hunter mesas rest on the beveled edges of a post-Raton formation syncline, showing a post-Eocene age. Much of the evidence for assigning a Quaternary age to the Raton basalts is physiographic: stream gravels which underlie some of the older flows are believed to be Pleistocene (Lee and Mertie, 1922, p. 8); certain alleged mastodon bones found in a well on Raton Mesa (Lee and Mertie, 1922, p. 9) indicate post-Tertiary age; and the physiographic evidence of the Folsom deposits given by Bryan (1929, p. 129; 1937, p. 149) supports a Quaternary age. The most definite evidence, however, appears to be the relationship of the basalt flows and the Ogallala formation discovered independently by Darton (1905, p. 178–179, Pl. 35) and the writer. Darton found Ogallala gravels of Pliocene age passing under the flows of Mesa de Maya in southeastern Colorado. The writer observed that the widespread

FIGURE 1. TERRACE CAPPED BY CLAYTON BASALT IN DRY CIMARRON CANYON
Eight miles N.W. of Folsom, Sec. 26, R. 29 E., T. 31 N. High mesa in left background is Emory Peak table capped by Raton basalt. Low line of trees at foot of terrace mesa, left middle distance, locates channel of Dry Cimarron River and long tongue of Capulin basalt. Canyon floor in foreground is Mesozoic sediments and Quaternary alluvium. View looking S.W.

FIGURE 2. CLAYTON LAVA — OGALLALA CONTACT
West of road cut northeast of Clayton, New Mexico, N.E. ¼, Sec. 30, R. 36 E., T. 27 N.

CLAYTON BASALTS

FIGURE 1. PALO BLANCO
From the southwest, showing central plug and rim of peaks.

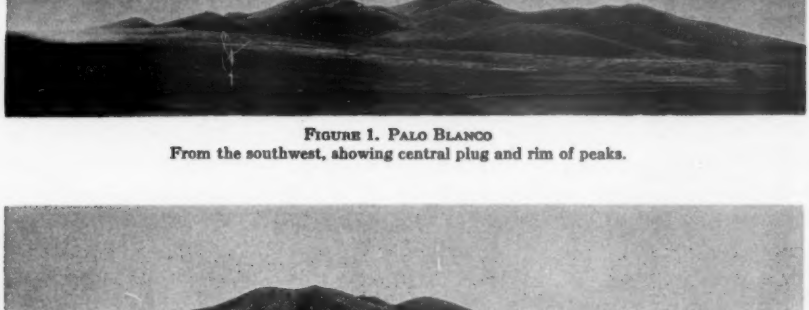

FIGURE 2. LAUGHLIN PEAK
Most perfectly preserved of the dacite type of cone. View from Mesa Llargo looking south.

FIGURE 3. PHONOLITE FLOW NORTH OF CHICO
Seen from the west. Typical rolling surface and irregular margin of jointed cliffs. Talus covers base of flow, valley floor is Quaternary alluvium.

DACITE AND PHONOLITE EXPOSURES

Ogallala sands of northern Union County are never found on top of basalt flows, although they are near laterally. On the Clayton-Cimarron Junction road 3 miles east and 7 miles north of Clayton, he has photographed the base of the lava flow resting upon Ogallala sands (Pl. 2). This paper gives the age of the basalts as Quaternary, ranging from early Pleistocene to Recent.

Heretofore two facts have caused some doubt of the Quaternary age: One is the large amount of dissection since the first lava outpouring: 2000 feet in the vicinity of Raton, 3500 feet at Fishers Peak in Trinidad, Colorado. Lee (Lee and Mertie, 1922, p. 13) has noted similar amounts of post-glacial erosion in northern Montana and western Colorado, and other examples can be cited. The other is the highly weathered condition of the dacitic cones of the district, formed midway in the series of basalt outpourings and much more severely eroded than the basalts. The evidence of the dacitic cones does not contradict a Quaternary age of the basalts for two reasons: (1) the cones are composed of rock whose structure and weathering characteristics are different from, and weaker than, the basalts, and (2) field comparisons of amount of erosion are invalid, being made either between dacitic cones and massive basaltic sheets of equal or greater age, or between dacitic cones and generally smaller basaltic scoria cones of younger age.

The writer assumes that Colfax and Union County basalt flows which have undergone the same physiographic history are contemporaneous. The basalts are grouped into the Raton, Clayton, and Capulin series partly upon this hypothesis, substantiated by Stobbe's petrographic studies. A weakness of the theory lies in its field application. Basalt flows in Colfax and Union Counties have been eroded in the same manner; the differences among flows of different ages are chiefly the differences in degree of relief of the basalt flow. For the youngest Quaternary (Capulin) flows, qualitative field evidence of the relief, or rather lack of it, is a sufficiently positive identification. But, although the Raton and Clayton basalts represent and preserve evidence of at least two distinct erosional stages of the region, a two-fold grouping must be made with caution. First, each group may represent not one single physiographic stage but a number of them, as is recognized by Lee and Mertie and the writer in the high level mesas of Raton lava between Trinidad, Colorado, and Johnson Mesa. The same may be true of the numerous Clayton basalt flows, although no quantitative data exist as evidence of it. Second, there is the danger of miscorrelation when areas being compared are not in lateral contact as, for example, physiographic correlation between Don Carlos Hills and Johnson Mesa. Both of these dangers will be largely overcome by more accurate quantitative data on the topographic surface; at the present time no contour map nor adequate elevation records are available for this area of over 4271 square miles so that physiographic correlation must be done qualitatively and caution observed in using the results.

Sequence of basalt flows.—Even a brief field examination reveals that the extrusive igneous rocks of northeastern New Mexico represent several different periods of flow separated by periods of fluvial erosion. The relative age of the flows, cones, and erosional intervals, all Quaternary, are determined by the topographic position of the various flows and extrusive masses. The Raton basalts were poured out on the extensive and essentially flat erosional plane formed subaerially during Tertiary time

on this portion of the Great Plains. Stream gravels rest on this surface and beneath the oldest basalt sheets (Lee and Mertie, 1922, p. 9). The pebbles, subround, stream washed, and largely composed of schists, granite, and gneiss, indicate an original source to the west in the core rock of the southern Rockies and deposition during Tertiary time before the erosion of the Raton basin. Subsequently a period of erosion lowered the elevation of the land surface which was not protected by basalt. The succeeding series of flows produced surface sheets in the newly formed lowland; these were then etched into mesas by more erosion, followed by more flows in the newest lowlands. The lava sheets therefore are found as caps on a series of mesas of varying elevations, the lower mesa caps represent successively younger flows. The most recent basalt flows are found in the floors of present-day valleys and have not yet suffered any appreciable differential erosion.

Lee and Mertie (1922), employing the physiographic reasoning given above, have established a series of four outpourings for the Raton quadrangle: two successive basaltic flows now found on the high mesas, followed by extrusion of nonbasaltic flows and cones, in turn succeeded by a series of basalt flows which now form low-level mesas.

This paper extends Lee and Mertie's physiographic reasoning and, with slight changes, their categories of lava flows eastward to the Texas line. One change is made necessary by the inadequacy of the best available base map of Union County. The two oldest basalt flows of Lee and Mertie, Qb^1 and Qb^2 on the folio's areal geologic map, are both cap rock of the high mesas and are separated by the comparatively small erosional interval of 300 feet. When using the hachured base map for the area east of Raton quadrangle and allowing for the regional decrease of relief of the pre-basalt erosional plane, it is impossible to distinguish with certainty between the two because of insufficient topographic data. Therefore, Lee and Mertie's categories Qb^1 and Qb^2 are here grouped under the term Raton Basalts and the symbol *Qbe*, without reflection on their validity. The second change, foreseen by Lee and Mertie (1922, p. 11), is the addition of the youngest series of basalt flows which occur in the valley bottoms east and south of Raton quadrangle although not in the quadrangle itself. These youngest flows and cones are termed Capulin basalts, and the symbol *Qbr* is employed. The third basalt series of the folio, there termed Qb^3 and found on low-level mesas, is described as Clayton basalts in this paper, and the symbol *Qbi* is employed for it. The practical field subdivisions of the basaltic flows of Union County at the present time are: as oldest and in general highest, the Raton basalts (*Qbe*), the Clayton basalts (*Qbi*), which typically form the extensive mesas of comparatively low relief, and the youngest or Capulin basalts (*Qbr*), which comprise the best-preserved cinder cones such as Capulin Mountain and the relatively linear or lobate flows proceeding from these cones down present-day valley floors.

General lithologic characteristics.—Olivine basalts predominate in all three ages, but the Raton flows are normal in olivine content and cap the highest tablelands and mesas. They are generally holocrystalline and everywhere micro-porphyritic, but in varying degrees. Olivine and rarely pyroxene form megascopic phenocrysts; the olivine is fairly fresh, although a few specimens showed evidence of hydrothermal alteration either to serpentine or iddingsite.

Clayton basalts have the widest areal extent and, within their own group and in comparison with the other flows, present the greatest textural and mineralogic variations. Scoria cones and thick lava sheets occur and the textures reflect these different forms in their range from glassy to coarsely crystalline and from sparsely to dominantly porphyritic basalts—olivine and pyroxene form phenocrysts and at times the feldspar shows a tendency toward phenocrystic development. Olivine basalts occur most frequently but grade occasionally to olivine-free basalts; in addition, unusual types occur, such as olivine basalts with quartz inclusions, basanites and feldspathoid basalts among which are haüyne basalts and nepheline basalts. Most of the olivine is fresh but occasionally iddingsite is found in megascopically visible amounts.

Capulin basalts have the smallest areal extent and are found as cones and thin tongues of lava which flowed down stream valleys. Scoriaceous lavas, bombs, and pyroclastics are common near volcanic cones and thin lava flows. These rocks are either finely crystalline or partly glassy and porphyritic. Mineralogically, all are olivine basalts; the olivine is generally quite fresh but iddingsite does occur in small amounts.

Outcrop and lithologic characteristics correlate with the three-fold division of the basalt flows. Raton flows are more massive, less scoriaceous, and usually have more soil cover. Clayton flows are more scoriaceous and closely jointed than Raton flows, less so than Capulin lavas, and have the most variable texture and mineralogy of the three flows. Capulin lavas are most scoriaceous and vitreous and least massive, have the most restricted and freshest outcrops and the least soil cover.

RATON BALSALTS

Lithologic characteristics.—As a group the Raton basalts are medium to dark-gray, predominantly fine-grained olivine basalts. Rarely (Valley P. O.), the texture becomes coarser to approach a diabase. The megascopic mineralogy is normal for olivine basalts. The Raton basalts are vesicular to compact; vesicles are commonly 1 to 2 mm. in diameter, rarely as large as 5 mm. Some flow structure is shown in the vesicular types, less in the dense, fine-grained types. Normal columnar jointing is found.

Alteration.—There has been little alteration of the Raton basalts except for some iddingsite. Some minor end-stage alteration of olivine to a serpentine-limonite aggregate in 2 localities is confirmed by Stobbe. There is the common iron stain from surface weathering, and calcite fillings locally in vesicles and joints.

Localities.—Devoy Peak (cone on small, high lava mesa 10 miles NE of Folsom, 6 miles E of Oak Canyon mesa. Also Emory Peak and mesa 4 miles NE of Folsom, and unnamed mesa on E wall of Briggs Canyon, 8 miles E of Folsom.) Specimen base Devoy Peak dark-gray to black, fine-grained, dense olivine basalt with 1–2 mm. iddingsites. Multiple flows, marked columnar joints. All three lava platforms rise above exposed Dakota sandstone near crest of regional anticline, and resemble Johnson mesa closely in elevation and dissection.

Valley P. O. (high mesa at Valley P. O., 22 miles E of Devoy Peak, extends N into Colo.) dark-gray olivine basalt. Top fine-grained vesicules 1–2 mm. dia. Bottom coarser-grained near diabasic. Good columnar jointing.

Johnson Mesa. (Large, high mesa between Raton and Folsom). Four localities described: W. edge top, fresh medium-gray vesicular olivine basalt; top of Manco Burro Pass, north edge, medium-

gray vesicular olivine basalt in upper layers, base of flow shows chilling, some interstitial glass and light-gray, highly vesicular layers; east end of mesa along Folsom road cut, top and bottom layers like Manco Burro Pass though coarser vesicles; southwest side gap between Johnson and Hunter mesas, medium-gray, vesicular to dense olivine basalt with 1–2 mm. iddingsites.

Mesa Llargo. (9 miles south of Johnson Mesa, Sec. 35, R. 26 E., T. 29 N. High L-shaped mesa capped by fine-grained, dark-gray, finely vesicular to dense olivine basalt). Top flat, no cone, 5°–7° slope to S.E. May be outlier of Johnson Mesa but has thinner soil. S. limit of Raton basalts in Colfax Co.

Hereford Park (rough country just east of Johnson Mesa, 9 miles W of Folsom, contains high mesa probably outlier of Johnson Mesa). Specimen from Sec. 25, R. 27 E., T. 31 N., fine-grained, dark-gray to black, dense olivine basalt. Normal weathering, some carbonate crusts. Mesa surface slope 7° S.E., residual soil cover.

Oak Canyon Mesa (high lava mesa 7 miles N. of Folsom, W. Union Co., strongly lobate in plan, correlated physiogr. with Johnson Mesa). Dark-gray, fine-grained, slightly vesicular and porphyritic olivine basalt specimen from head of S. Fork of Oak Canyon.

CLAYTON BASALTS

Lithologic Characteristics.—Clayton basalts include at least four varieties of basalt, further study may identify more. At least 75 per cent, by estimate, are medium-gray, fine- to medium-grained, slightly vesicular olivine basalts, occurring as surface flows and scoria cones. Medium-grained specimens show small crystals of olivine, gray plagioclase, and augite to the naked eye. Flow surfaces are vesicular to scoriaceous, crusty and only slightly weathered; they show crude columnar jointing and, between Des Moines and Clayton, evidence of lava tunnels. Many high-angle scoria cones of Clayton basalt occur with the flows. Megascopically their material is fine-grained black scoria, which rarely shows traces of glass. The cones are breached in the southwest quadrant.

In addition to normal basalts, olivine-free basalt and olivine basalt with quartz inclusions occur. Further, Stobbe has identified feldspathoid basalts and basanites with the microscope.

Alteration.—Surface weathering has altered the magnetite of the scorias and most vesicular flows to a red-brown iron oxide, less vesicular flow rock tends to remain black. Rarely, in hand specimens, iddingsite crystals and brown alteration stains are visible around large olivines. Except for scorias, Clayton basalts are largely unaltered and unweathered.

Localities.—The following descriptions are arranged, for convenience only, to correspond to four major geographic areas included in the paper.

1. Northwest section; in eastern Colfax Co. Includes Yankee Volcano, Eagle Tail Mtn., Black Mesa, and outlier east of Meloche Mesa, and Hunter Mesa gap.
2. Southwest section; south of the above and in eastern Colfax Co. Includes Blosser Mesa and Gap, Twin Craters, Temples Peak area and Tafoyah, Joe Cabin Arroyo, and a small knoll 14 miles south of Joe Cabin Arroyo near Pittsburgh.
3. Central section; in Union Co. Includes some Sierra Grande flows, the large mesa, and its outliers, from Des Moines to Clayton, and Don Carlos Hills.
4. North section; northwest, north and northeast of Sierra Grande. Includes Hereford Park area west of Folsom, Robinson Mtn., Burnt Mtn., some flows of Emory Peak, a mesa in Dry Cimarron valley, and the volcano at the head of Briggs Canyon.

NORTHWEST SECTION:

Yankee Volcano and outliers. (6 miles NE of Raton, west base of Johnson Mesa). Cone proper specimen is medium- to dark-gray, fine-grained olivine basalt containing numerous corroded quartz grains (Lee and Mertie, 1922, p. 10), visible with hand lens, possibly incorporated by lava in passage through local sandstone beds. Cone is low-angle shield type, 300 ft. relief. Specimen from lava cap of 2nd outlier W. very similar or identical to above. Specimen from wash 300 yd. W. of 2nd outlier shows nepheline (Stobbe, 1949, p. 1060) and quartz xenocrysts.

Black Mesa. (Small mesa 7 miles S.W. of Johnson Mesa). Relief approx. 400 ft. Specimen top of N.E. side is dark-gray, fine-grained to porphyritic, vesicular olivine basalt with small phenocrysts olivine, augite and plagioclase. Lee and Mertie (1922, p. 10) call similar specimen from Black Mesa "normal type of" olivine basalt.

Outlier. (1 mile E. of Meloche Mesa, elongate table 1½ miles N-S. Top surface higher than but correlated with Black Mesa physiograph. Mertie (Lee and Mertie 1922, p. 10) calls this rock augite andesite and says source is low hill north of Meloche Mesa). Several specimens examined: Medium-gray, fine-grained, usually dense, but locally with 1.–4. mm. vesicles augite plagioclase rock here called olivine-free basalt. One specimen shows flow structure.

Hunter Mesa gap. (Low hill at N. end Hunter Mesa, Sec. 4, R. 25 E., T. 30 N.). Three specimens examined: black, fine-grained, slightly vesicular rock identified by Mertie (Lee and Mertie, 1922, p. 10) and Stobbe as haüyne basalt. Other specimens from N. and S. walls of gap are medium-gray, fine-grained olivine basalts.

SOUTHWEST SECTION:

Blosser Mesa and Gap. (Main mesa ½ mile S. of Green Mtn. covers 6 square miles, long extension runs W. through Gap and S. to E. foot of Eagle Tail Mtn.; small outlier 2 miles E. of Green Mtn. N. and E. rim of mesa cliffed, S. and W. boundary obscure in broad stream divide). Specimen from mesa proper is medium-gray, fine-grained, dense to slightly vesicular olivine basalt with good flow structure. Specimen from small cone at Gap is medium-gray, fine-grained olivine basalt with weak flow structure and a few visible olivines. Specimen from outlier, Sec. 13, R. 25 E., T. 29 N., dark-gray, fine-grained, vesicular and carbonate encrusted olivine basalt.

Eagle Tail Mountain. (Large cone and mesa 10 miles S of Black Mesa, 16 miles S. of Raton, west limit of Clayton basalts). Rock is dark-gray, fine-grained, dense olivine basalt. Hand specimens show small olivine and augite crystals, and surface weathering to red iron oxide coloring and some arid-climate calcite crusts. N.E. extension of Eagle Tail Mesa may merge with Blosser Mesa W. of Blosser Gap, but outcrops are obscure.

Twin Craters (two scoria cones 9½ miles S.E. of Blosser Mesa, Sec. 16, R. 26 E., T. 27 N.). Specimen from north cone is medium-gray, fine-grained to porphyritic olivine-free basalt (or pyroxene andesite) with 1. to 4. mm. vesicles. Visible phenocrysts of plagioclase and augite. South cone appears to be Capulin basalt.

Temples Peak and J. T. Rincon area (breached laccolithic (?) dome 1¾ miles in diameter, 3 miles S.E. of Twin Craters, 2 miles E. of Chico, eastern Colfax Co.). Two Clayton flows: long flow from Joe Cabin Arroyo to N.W. rim of basin of breached dome (J. T. Rincon) and broad flow on bottom and E. side of J. T. Rincon; both flows locally cover tilted and eroded Cretaceous sediments of dome. Several specimens examined are medium-gray, fine-grained, or dense olivine basalt.

Joe Cabin Arroyo (3 mile canyon, 2 miles S. of Twin Craters, 4 miles N. of Chico, Sec. 27, R. 25 E., T. 27 N.) Two Clayton sheets found on top of N.W. and S.E. walls, probably same flow from N. Twin Crater. Two specimens are medium-gray, vesicular olivine basalt, one is fine-grained other has prominent phenocrysts of plagioclase, olivine, augite.

Pittsburgh knob (extrusive knob, 175 yd. long by 75 yd. wide, 2 miles N.E. of Pittsburgh, W. ½ sec. 36, R. 26 E., T. 25 N., eastern Colfax Co.). Hand specimens are dark-gray to black, fine-grained, dense, analcime basanite (Stobbe) whose weathered surface has irregular nodular pattern. Field relationships obscure; knob is a compact outcrop of black basaltic rock surrounded

by undisturbed Cretaceous and Tertiary sediments. May be small surface leak from shallow intrusive body.

CENTRAL SECTION:

Sierra Grande, largest cone in northeast New Mexico, stands on a low mesa, 16½ miles northeast of Joe Cabin Arroyo, immediately south of Des Moines near the Colfax-Union County boundary. Although the cone is mainly andesitic or dacitic, it has been a vent for every phase of igneous extrusion with the possible exception of the earliest or Raton basalt flows; its structure is complex and largely unknown. On the west flank short flows of feldspathoidal basalts are known, on the west, south and east flows of Clayton olivine basalt merge with the large Folsom-Clayton mesa, and on the northeast a vent on the flank has poured out a 12-mile tongue of the youngest or Capulin basalts. A specimen of the Clayton olivine basalt collected from the east flank is black, fine-grained and finely vesicular with carbonate in some vesicles. The rock is typical of the extensive Clayton flows between Sierra Grande and Clayton and represents that fraction of the Sierra Grande complex. Another Clayton specimen collected from the lower part of the cone on the northwest shoulder is a dark-gray, fine-grained, finely vesicular olivine-free basalt or pyroxene andesite.

Folsom-Clayton Mesa. Between Folsom and Clayton near the Texas line, a low mesa of Clayton basalt extends for 52 miles and covers more than 400 square miles. Its top is generally flat to gently undulating and is dotted with small intermittent lake basins. The mesa rim is precipitous, 200–400 feet high, and frequently lobate in a pattern which indicates the original boundary of the lava flows rather than post-eruptive stream erosion. The longer lobes suggest that their lavas were poured into the stream valleys which were the predecessors of Rafael Creek, Cieneguilla del Burro Creek, Rabbit Ear Arroyo, Perico Creek, and Carrizo Creek. Three large scoria cones, Mt. Clayton, Mt. Dora, and Rabbit Ear Mountain, and several smaller unnamed cones are evenly distributed over the mesa. No field evidence has been found for the vents of the large amount of lava of this mesa, except the obvious cinder cones which appear to be inadequate. There is a hint of a northwest-southeast alignment of cones through Mt. Clayton and again through Mt. Dora, which suggests fissure eruption through dikes now concealed by lava. Specimens were obtained from the following localities: 1½ miles west of Clayton on highway, near southeast end of flow Sec. 21, R. 35 E. and T. 26 N; from Sec. 15, R. 34 E., T. 26 N., on highway 7 miles west of Clayton, on a narrow tongue of basalt between Rabbit Ear Arroyo and Perico Creek; from Sec. 34, R. 32 E., T. 27 N., on highway 4 miles due east of Mt. Clayton; and from Sec. 18, R. 21 E., T. 28 N., on highway halfway between Grenville and Des Moines, 10 miles southeast of Sierra Grande. In hand specimens the rocks are medium-gray, fine-grained, vesicular basalts with olivine phenocrysts, in one case as long as 5 mm. with some carbonate encrustation and vesicle filling.

NORTH SECTION:

Robinson Mountain (scoria cone 6 miles N.W. of Sierra Grande). Specimen from cone is black, fine-grained nepheline basalt described by Stobbe. Two specimens from flows in canyon ¾ mi. N. of mountain are medium-gray, fine-grained or dense, scoriaceous olivine basalts.

Burnt Mountain (scoria cone 7 miles W. of Robinson Mountain). Specimen from N.E. flank of cone is black, fine-grained, scoriaceous, olivine basalt, weathered red. Specimen from W. crater wall is dark-gray to black, fine-grained, vesicular olivine basalt with visible olivines and plagioclase laths. Specimen from W. side of hogback of N.W. second flow from Burnt Mountain is medium-gray, fine-grained olivine basalt.

Emory Peak (basalt cone on high mesa 4 miles N.E. of Folsom, Sec. 33, R. 29 E., T. 31 N.) A specimen of its repeated and varied Clayton phase flows is medium- to dark-gray, fine-grained, olivine basalt. Emory Peak flows into Dry Cimarron canyon are among key evidence for basalt chronology in area.

Cone near head of Briggs Canyon (scoria cone 6 miles S.W. of Folsom, Sec. 24, R. 29 E., T. 30 N.) Specimen from cone is a typical medium- to fine-grained volcanic breccia of fragments of scoria, pink sandstone and white limestone. Hand lens shows corroded quartz grains possibly picked up by lava while passing through local sandstone.

CAPULIN BASALTS

Lithologic Characteristics.—Capulin basalts are dark-gray to black, vesicular to scoriaceous olivine basalts, containing plagioclase, olivine, and magnetite, often with small plagioclase phenocrysts. Capulin flows are found in five localities within 25 miles of Mt. Capulin. Outcrops are relatively fresh and unweathered, are rarely etched into relief, and usually preserve the disorganized surface of flowing lava. Landes' (1928, p. 931) correlation of Kansan ash beds with Capulin eruptions is to be noted. No evidence of an acidic magma phase of Capulin or Clayton lavas has been found by the writer. Red Mountain dacites would seem, from a chemical point of view, a better source for the Kansas material.

Alteration.—Scoria in Capulin cones is red because primary magnetite has oxidized to red ferric oxides; the same effect is less evident on surfaces of ropy flows. Locally, coatings and vesicle fillings of calcium carbonate are found, characteristic of arid climate weathering. Compared with Raton and Clayton flows, Capulin basalts are fresh and unaltered.

Localities.—Capulin Mountain and flows. (scoria cone 5 miles S.W. of Folsom. Many flows around base and one long flow N. and E. 21 miles down Dry Cimarron canyon. The cone itself is a National Monument and an excellent example of scoria volcano; it is unbreached, almost undissected, has a good crater, and road cuts on its flanks show well-bedded pyroclastics and occasional caliche layers at about 32° dips.) (1) Specimen from bottom of crater is dark-gray to black, fine-grained porphyritic with small plagioclase crystals, vesicular olivine basalt in large blocky boulders; (2) typical scoria bomb from W. crater rim is dark-gray to black, fine-grained, coarsely vesicular olivine basalt weathered red; (3) specimen, from W. rim, is 6 in. block of buff sandstone inside 1-inch shell of olivine basalt. Four specimens from flows: one from end of 21-mile Dry Cimarron flow and typical is black, fine-grained with 4 mm. olivine phenocrysts, vesicular olivine basalt; flow specimens from Sec. 17, 20, and 21, R. 28 E., T. 30 N., are dark-gray, fine-grained to porphyritic, vesicular olivine basalts, with phenocrysts of plagioclase, augite and olivine. One pyroclastic specimen from W. bank of road cut 3 miles N. of Folsom is a cemented tuff made of black basaltic glass and buff friable limestone fragments 2–6 mm. across in buff calcium carbonate cement.

Horseshoe Crater. (Scoria cone 7 miles S.W. of Capulin Mountain and small flow). Specimens are weathered red scoria of dark-brown to black, fine-grained, vesicular to scoriaceous olivine basalt.

Twin Craters, south cone. (9½ miles S.E. Blosser Mesa. N. cone described under Clayton basalts). Specimen from top of S. rim of crater is dark-gray, fine-grained vesicular olivine basalt showing some flow structure and light plagioclase phenocrysts.

Mt. Marcy (scoria cone and flow 7 miles S.E. of Horseshoe Crater and 5 miles S.W. of south base of Sierra Grande. Flow extends 3 miles S. and 5 miles E. from cone.) Specimens of cone are weathered bombs of dark-gray, fine-grained, scoriaceous olivine basalt. Flow specimens are black, fine-grained, vesicular olivine basalt with small plagioclase phenocrysts. Some arid-climate calcite crusts. Rock much like that of Capulin and Horseshoe.

Van Cleve flow. (19 mile flow from N.E. flank of Sierra Grande E. and N.E. to Van Cleve, Sec. 7, R. 32 E., T. 29 N.). Specimens are dark-gray, fine-grained vesicular olivine basalt.

OTHER IGNEOUS ROCKS

RED MOUNTAIN DACITES

Distribution.—A widespread series of extrusive and intrusive hornblende dacites in northeastern New Mexico is recognized as a lithologic unit, and named in this paper the Red Mountain dacites after the type locality of Red Mountain (also called Bell Mountain) on Johnson Mesa in eastern Colfax County. Other outcrop areas include Towndrow Peak, Green Mountain, Cunningham Butte, Laughlin Peak, Palo

Blanco, Raspberry Peak, and Sierra Grande. Red Mountain dacite may be present in the Turkey Mountain-Slagle Canyon area west of Chico.

General lithologic characteristics.—Red Mountain dacite flows exhibit uniformly whitish to light-gray, fine-grained nonvesicular hornblende dacite indistinguishable megascopically from hornblende andesite. The rock has a few plagioclase phenocrysts 10 mm. or less in length and large numbers of hornblende needles, up to 2 mm. long, throughout the rock. The groundmass contains plagioclase, magnetite dust, and a large amount of light-colored glass (Stobbe, 1949, p. 1070). Mertie (Lee and Mertie, 1922) and Stobbe (1949) have shown that chemically the rock is a dacite. Red Mountain dacite weathers about .2 inch deep to a characteristic pinkish-red in the glassy bands, the balance of the rock remaining gray; the result is a marked display of the flow structure of the cooling lava. Although there are minor but definite petrological variations in Red Mountain dacite collected from different localities, none indicate more than local differences in physical conditions of cooling and the accompanying shifts in mineral composition.

Age relationships.—Red mountain dacite is intermediate in age between the Raton basalts and Clayton basalts. Towndrow Peak and Red Mountain are younger than Raton flows of Johnson Mesa because they rest on them, and the boundary relationship between Red Mountain dacites and Clayton basalts at the base of Palo Blanco and the southeast flank of Sierra Grande indicate that Clayton basalts are younger and cover Red Mountain dacites. The Chico phonolites fall into the same age bracket, post-Raton and pre-Clayton, and presumably are approximately contemporaneous with Red Mountain dacites; erosional details and physiographic development of the two rocks further strengthen this belief.

Localities.—*Red Mountain* (eroded dacite cone on Johnson Mesa, Sec. 22, R. 26 E., T. 31 N.). Base diameter 1 mi., top about 500 ft. above mesa. No crater remains, flanks gullied and covered with thin soil and hornblende dacite joint blocks. All specimens are light to medium-gray, fine-grained, porphyritic hornblende dacite as described. Lee and Mertie (1922, p. 10) describe a Towndrow Peak specimen and give a chemical analysis of a similar rock from Red Mountain. This analysis, together with Stobbe's (1949, p. 1067) are the basis for naming the rock dacite; megascopically it is indistinguishable from hornblende andesite.

Towndrow Peak (eroded dacite cone on Johnson Mesa, Sec. 23, R. 25 E., T. 31 N.). Same size, surface features, and lithologic character as Red Mountain. No surface expression of dikes is found near Towndrow Peak or Red Mountain and the conclusion is that both cones were built over conduits rising through Johnson Mesa after the extrusion of Raton basalts.

Cunningham Butte. (9 miles S.W. of Towndrow Peak, Sec. 36, R. 24 E., T. 30 N.). An elongate plug set in a dike striking N.W. Lee and Mertie (1922, p. 10) say cap of butte may be remnant of a flow. Specimens are white to light-gray, fine-grained, porphyritic hornblende dacite, weathered pink. Flow structure more obscure and rock coarser-grained than type locality.

Green Mountain (11 miles S. of Towndrow Peak, Sec. 15, R. 25 E., T. 29 N.). Specimens are light-gray, fine-grained, porphyritic hornblende dacite which weathers pink to red and shows flow structure. The cone is symmetrical, lacks crater, and is gullied like other Red Mtn. dacite cones.

Laughlin Peak (large, eroded, dacite-type cone 8 miles S.E. of Green Mountain and 11 miles N. of Chico, R. 26 E., T. 28 N.) Base diameter 3½ miles, relief over 1200 ft. Largest volcano (Pl. 3) in area except Sierra Grande. Many large ravines on flanks leaving prominent shoulders and spurs. No crater shows although dikes and plug-like masses outcrop in the high center. Cone has relatively few bedrock exposures and is covered with thin soil and many dacite joint blocks. Specimens from N.E. and S. shoulders are light-gray, fine-grained, slightly vesicular hornblende dacites with a few

plagioclase phenocrysts and many hornblende needles in groundmass. Weathers into pink and gray bands showing strong flow structure. Specimens from top of mountain are similar but lighter gray and have less hornblende.

Palo Blanco (eroded cone 8 miles S.E. of Laughlin Peak and 13 miles S.W. of Sierra Grande, R. 27 E., T. 27 N.) Base diameter 2½ miles, relief about 1000 feet. Has high center peak surrounded by deep annular valley rimmed by circle of high peaks (Pl. 3) only slightly lower than center. On outer E. and N.W. flanks are large upturned blocks of Cretaceous sediments which are sometimes shattered and show contact metamorphism. Their contacts are not visible and their structural relation to the mountain is not known. The slopes of Palo Blanco, except for the highest peaks, are covered with talus, thin soil, and dacite joint blocks. Specimens from center, and E., S., W. and N.W., flanks are typical Red Mtn. dacite: light-gray, fine-grained porphyritic hornblende dacite weathered pink, showing flow structure. The center peak is slightly coarser textured.

Raspberry Peak (small eroded cone 5 miles S. of Laughlin Peak, 8 miles W. of Palo Blanco, Sec. 18, R. 26 E., T. 27 N.). Specimens are light-gray, fine-grained, porphyritic hornblende dacite with plagioclase phenocrysts and fine hornblende needles. Weathers pink to show flow structure. Cone is gullied and crater is gone; it apparently stands on a Chico phonolite flow, although contacts are talus covered, and cone may be younger than phonolite.

Sierra Grande (largest volcano in New Mexico, S. of Des Moines. Unique in area for size and complexity. Upper surface relatively inaccessible and unexplored). Deep stream valleys cut the flank into high spurs and ridges which converge at the central peak. No crater is visible from base although Lee (1912, p. 360) alludes to one. Higher divides are bare bedrock, their slopes bare talus blocks; lower slopes have thin soil and talus block cover supporting grass and brush. Complex make-up of Sierra Grande shown by specimens collected: Capulin olivine basalt in place on N.E. flank, Clayton olivine basalt in place on S.E. slope, Clayton olivine-free basalt in place on S.W. and W. flanks, and Red Mtn. dacite float on N. slopes. Latter rock is typical in hand specimen being a light-gray, fine-grained, porphyritic hornblende dacite which weathers pink and grey. Present knowledge of Sierra Grande's lithology, structure and physiography indicates large part of cone is Red Mtn. dacite, but more field work is needed.

TURKEY MOUNTAIN ANDESITE

Turkey Mountain is an igneous complex located at the head of Slagle Canyon in Sec. 16, T. 27 N., R. 25 E., 8 miles northwest of Chico in eastern Colfax County, and appears to be a shallow laccolith or apophysis which has formed a dome structure whose lavas have broken through to the surface at several places. It is closely related to the igneous complex of near-by Slagle Canyon. Until more field studies are made, it is not known whether hornblende andesite is the dominant rock of Turkey Mountain or a differentiation fraction.

A specimen collected by the writer from the southwest flank of Turkey Mountain has been identified by Stobbe (1949, p. 1071) as hornblende andesite. In hand specimen, the rock is gray-green, fine-grained, porphyritic with ferromagnesian phenocrysts up to 10 mm. long forming 50 per cent of the rock. The groundmass is fine-grained plagioclase, magnetite dust, and pyroxene.

SLAGLE TRACHYTES

Distribution.—Soda trachytes have a restricted area of outcrop characteristic of sills and dikes, and are found in only four localities, all in the southwestern part of the area: Slagle Canyon, Red Hill, Joe Cabin Arroyo, and Turkey Mountain. The outcrops are grouped in a 10-mile radius and, from the similarity of their lithologic character and field relations, are believed to form an igneous sub-unit closely related

to the Chico phonolites in the same district. They are named Slagle Trachytes from the exposures in Slagle Canyon, Sec. 4, T. 26 N., R. 25 E.

Lithologic characteristics.—Megascopically the Slagle trachytes are light-tan, fine-grained porphyritic rocks with phenocrysts of chalky feldspar and abundant hornblende needles. The hand lens reveals considerable magnetite dust in the groundmass. Weathering produces a reddish to brown surface. Flow structure shows in the arrangement of the hornblende needles of some specimens.

Localities.—A soda trachyte sill is exposed in the east wall of Slagle Canyon, 1 mile north of the bridge in the Maxwell-Chico road. The rock is light tan, fine-grained, and porphyritic with phenocrysts of chalky feldspar and hornblende. The groundmass is composed of light feldspars, some fine hornblende needles, and considerable magnetite dust.

Soda trachyte is found in an outcrop at the base of the east side of Red Hill, 1 mile east of Slagle Canyon in Sec. 2, T. 26 N., R. 25 E. It is a pale gray, fine-grained, porphyritic rock with chalky feldspar phenocrysts and needles of pyroxene and considerable magnetite dust. It weathers tan to brown. The outcrop is probably part of a sill; contacts are covered.

The top of the south wall of the central section of Joe Cabin Arroyo, in Sec. 28, T. 27 N., R. 26 E., exhibits Slagle trachyte which resembles that of other localities lithologically except that the groundmass is slightly coarser and there are fewer ferromagnesian minerals. The rock is tan to light gray, fine-grained, and porphyritic with some feldspar and less pyroxene phenocrysts. Considerable fine magnetite is present in the groundmass. The outcrop is probably part of a sill.

Soda trachyte is found above a lava flow on the north side of Turkey Mountain. It is a light-gray, fine-grained, porphyritic rock with phenocrysts of feldspar. Ferromagnesian minerals are scarce and some light mica, sericite, or muscovite is present; magnetite dust shows in the groundmass.

CHICO PHONOLITES

Distribution.—Chico phonolites occur abundantly in a triangular area between Laughlin Peak, Temples Peak, and Turkey Mountain, in eastern Colfax County. A few exposures reveal sills and dikes, but the majority are mesa-like remnants of surface flows. Here are found all the extrusive phonolites known in the region, and all the intrusive phonolite masses known except some 8-inch sills in the north wall of Dry Cimarron Canyon, 11 miles east of Devoy Peak. The principal phonolite masses are Kiowa Mesas, an unnamed flow at south foot of Laughlin Peak, and the Timber Butte plugs and flows west of Palo Blanco. In the southeast several large flows radiate from the J. T. Rincon: Pecks Mesa, Temples Peak, and associated flows west to Chico and north to Joe Cabin Arroyo, unnamed flow on north rim of J. T. Rincon, and The Ragged End, a high table east of the rincon. In the southwest are the Slagle Canyon and Turkey Mountain complex of intrusives and extrusives, and the high remnant of Tenaja Mountain. The vents of Chico phonolite flows are concealed; one was certainly located over the J. T. Rincon, another probably is to be found on Turkey Mountain, and a third on the Timber Buttes.

The Temples Peak region, centered on the J. T. Rincon, is structurally a sharp,

slightly elliptical dome, 1¾ miles in diameter, which has been deeply breached to form a physiographic bowl. The inner walls of the bowl or rincon are precipitous and reveal a nearly complete sequence of Mesozoic sediments of the area, beginning at the top with Dakota sandstone and including Purgatory sandstone, a thin sandy phase of the Morrison formation, 45 feet of sugary sandstone probably equivalent to the Exeter sand of Dry Cimmaron Canyon, and over 200 feet of Dockum conglomerate, sandstone, and shale. In the center of the basin, underlying the Dockum horizontally is an unfossiliferous, coarse, white-quartz-pebble conglomerate of an all-over cream to buff color which weathers brown to dark brown. It is strongly lithified and locally jointed into large blocks. The total exposed thickness is 19 feet, including 2 feet or less of an underlying gray-brown sandstone member whose base is covered. The only other known exposure of this formation is in the upturned sediments on the east flank of Palo Blanco. The formation is here named the Temples Peak formation after its type locality in the bottom of the rincon or bowl at the east base of Temples Peak.

Phonolite flowed down the flanks of the J. T. Rincon dome before erosion. Deep erosion of the dome to a bowl was followed by the inflow of two flows of Clayton basalt. In the northwest quadrant basalt barely flowed over the rim, but on the east side of the rincon basalt flowed down from the north to cover a large part of the floor of the rincon. It is possible that the phonolite vent is covered by this basalt sheet.

Lithologic characteristics.—The Chico phonolites are green, fine-grained, porphyritic, soda-rich extrusives and intrusives whose feldspar phenocrysts are large (5–10 mm.), tabular, and parallel to evident flow lines, and etched into knobby relief by weathering. More rarely the phenocrysts are small (2 mm. or less), and merge into the ground mass. The very fine-grained groundmass rarely shows any minerals recognizable in the hand specimen, but Stobbe (1949, p. 1073–1076) has demonstrated that the composition is soda orthoclase, nepheline, analcime, and aegirine.

Weathering of the Chico phonolite shows a characteristic layering parallel to the flow surfaces which cracks the rock mass into irregular laminae from 1 to 3 inches thick. The cracks run well back from the surface and show calcite or alkali crusts. A system of vertical joints is present and is readily attacked on the edges of flows, producing sharp re-entrant ravines of varying length. The upper surface of the phonolite flows is gently undulating to irregular, in contrast with the flat surface of basalt flows; soil cover is thin and tetrahedral joint blocks of phonolite are plentiful. The topography of Pecks Mesa and the flows north and west of the J. T. Rincon suggest that the phonolite lava was more viscous and thicker than the basalt flows and solidified with a lobate boundary pattern (Pl. 3).

Localities.—Kiowa Mesas. (4 miles E. of Laughlin Peak). Phonolite flow erosion remnants on open plain. Specimens are dull-green, vitreous to fine-grained, porphyritic phonolite with 3 to 4 mm. white feldspar phenocrysts. Outcrops are markedly weathered on the numerous joints and flowage planes. Specimen from near-by flow at S. base of Laughlin Peak is dark-green, vitreous, very dense phonolite with strong flow structure.

Timber Buttes. (3 eroded cones or plugs 2 miles S.E. of Laughlin Peak. 4 miles S. of Kiowa Mesas). Specimens green to gray-green, fine-grained, porphyritic phonolite with tabular white feldspar phenocrysts and visible aegirine needles, weathering to typical bumpy, irregular surface because of harder phenocrysts. Timber Buttes probably vents for local flows although contacts are covered.

Temples Peak flows. (W. rim of J. T. Rincon Sec. 11, R. 26 E., T. 26 N. and flow area 3 miles N. and W.) All specimens collected are bright to gray-green, porphyritic phonolite with white orthoclase phenocrysts and abundant aegirine. Zoning in the feldspars, and flow structure and thin, platy parting are evident and characteristic, as are numerous minor variations of texture and structure. A small vesicular phonolite dike at S. base of Temples Peak has thin calcite crusts lining the vesicles which are filled with thin, brown petroleum. Topography of the flows is gently rolling with sharp canyons; boundaries are lobate in plan, and rise as abrupt rounded hill forms with many re-entrants. Upper surface covered with thin soil and many tetrahedral joint blocks.

The Ragged End. (Mesa east of J. T. Rincon, 2½ miles long E.-W., 2 miles N.-S. R. 27 E., T. 26 N.) Specimens gray-green, fine-grained, porphyritic phonolite with white feldspar phenocrysts. E. flow from J. T. Rincon dome vent and eastern limit of known phonolite outcrops.

Pecks Mesa. (200–400 feet high mesa 1½ miles in diameter, 4 miles S. of Temples Peak). Specimens from S. edge, center top, W. and N. edges are uniform dull gray-green, fine-grained, porphyritic phonolite with white orthoclase phenocrysts and fine aegirine. Groundmass weathers gray, feldspars become chalky, and platy flow parting becomes evident. Appears to be S. flow from J. T. Rincon outlet. An analcime microfoyaite dike (Stobbe, 1949 p. 1081) rises 100 feet above the mesa top on its east edge to make a fin-like ridge 1 mile long, which strikes N-S. Its contacts are talus covered.

Turkey Mtn. flows. (4 flow areas around Turkey Mtn., 9 miles N.W. of Temples Peak: small sheet at W. base of Turkey Mt.; long, lobate-plan flow at N. base of Turkey Mt. extending E. to Raspberry Peak; broad flow E. of Turkey Mtn. extending from Raspberry Peak S. to S. end of E. wall of Slagle Canyon, including Red Hill; and a lobate-plan flow extending from S. base of Turkey Mtn. 2 mi. S. on W. wall of Slagle Canyon and flooring its N. end). Specimens are gray-green, fine-grained porphyritic phonolites with much local variation in size of orthoclase phenocrysts and strength of flowage parting. Two specimens from Red Hill, (Sec. 2, R. 25 E., T. 26 N.) are medium-gray, fine-grained phonolite with marked flow structure, and are very similar to rock on north point of Temples Peak. The top surfaces of the flows undulate gently and are covered with thin soil and many phonolite joint blocks.

A sill (Pl. 4) of dark-green, very fine-grained tinguaite, 3–17 feet thick is exposed in both the E. and W. walls of Slagle Canyon, 2 miles N. of the Chico road, Sec. 34, R. 25 E., T. 27 N. A microfoyaite sill is found in the walls at the W. end of Joe Cabin Arroyo, and a small plug-like knob of related rock occurs in Sec. 5, R. 26 E., T. 26 N., 2½ miles N. of Chico.

Tenaja Mtn. (High erosion remnant in Sec. 14, R. 24 E., T. 28 N.). Specimen from small phonolite cap-rock area is gray-green, fine-grained, porphyritic phonolite with white orthoclase phenocrysts. Lower slopes are Upper Cretaceous Apishapa shales. Tenaja is western limit of Chico phonolites.

DIKE ROCKS

Classification and distribution.—The dikes in northeastern New Mexico are grouped in three categories on the basis of lithologic characteristics and field relationship:

A. Basaltic feeder dikes associated with Raton and Clayton basalts.

B. Leucocratic, nonbasaltic dikes associated with Red Mountain dacites, Slagle trachytes, and Chico phonolites.

C. Melanocratic, basic dikes not known to be associated with existing surface flows.

Dikes of group A are poorly exposed in heavy talus cover on the sides of the basalt mesas. They are not treated in this paper. Dikes of group B are found in the southwestern part of the area in Slagle Canyon, southwest of Slagle Canyon, at the southern base of Temples Peak, and in the Pecks Mesa ridge or "fin". Dikes of group C are located south of Blosser Gap, in the west wall at the south end of Slagle Canyon, and in the broad flats south of Tres Hermanos in T. 27 N., R. 24 E.

Lithologic characteristics.—The composition of the leucocratic dike rocks of group

FIGURE 1. TINGUAITE SILL, SLAGLE CANYON
Near south side of Turkey Mt. dome. View from east. 17 feet of tinguaite exposed at base, overlain by Cretaceous shales; 30 feet trachyte flow at top.

FIGURE 2. LAMPROPHYRE DIKE, CHICO ROAD, SLAGLE CANYON
Dike is heavily weathered; has moderate thickness of altered shale and limestone at margins. Obscure as topographic feature.

SLAGLE CANYON INTRUSIVES

B is similar or occasionally identical with the near-by extrusive rocks, and it is reasonable to believe that these dikes are genetically related to the surface flows. Although weathered and frequently severely jointed, the dikes are on the whole well preserved. Their thickness varies from a few inches to 40 or 50 feet, rarely to nearly 100 feet. Surface weathering and erosion have left the dikes standing in high relief, boulders and blocks from the dikes are found near by as residuals and occasionally especially from the large dike south of the Chico Maxwell Road, in the wash of some of the larger streams. Most dikes are nearly vertical; contact metamorphic zones vary with the size of the dike, but are commonly thin and measured in a few inches. The dikes appear to have issued from the same magmatic reservoir that supplied the other nonbasaltic intrusives and extrusives.

The melanocratic dikes of group C are basic, many are lamprophyric, and all are sharply contrasted in composition and appearance with the first group. They have a consistent east-west strike, a regional phenomenon of the group reflected in the strike of several similar dikes 30 and 40 miles to the west in the foothill country of the Sangre de Cristo range. These basic dikes are severely weathered and rarely rise above the general level of the country; more often they have weathered out to a shallow, obscure depression. Weathering of the dikes transforms the mass of the rock into irregular nodules heavily stained with iron oxide and penetrated by innumerable fine cracks. It is common to find the contact selvage more resistant than the dike rock itself. The width or thickness of this group of dikes is fairly consistent, between 10 and 18 feet; no very thin ones are known, although this may be explained by their obscurity when weathered.

Localities: Leucocratic dikes.—Hornblende dacite from a dike striking southwest from the Chico road on the east side of Slagle Canyon is light gray, medium fine-grained, with numerous small needles of black hornblende. This rock strongly resembles Red Mountain hornblende dacite.

Two microfoyaites essentially alike were collected, one from a dike striking southwest from the Chico road on the east side of Slagle Canyon, and the other from a dike in the floor of Slagle Canyon, south of Chico road. These rocks are aphanitic and a light-greenish gray, very similar to the microfoyaite sill in Slagle Canyon, and have been named analcime microfoyaite by Stobbe (1949). Another analcime microfoyaite (Stobbe, 1949) forms the ridge on the Pecks Mesa.

A large dike in structural alignment with the Slagle Canyon complex but 4 or 5 miles to the south, is a porphyritic phonolite. The dike dips 90°, strikes N. 13° E. and outcrops intermittently for over 4 miles from a point in the S.E. $\frac{1}{4}$ of Sec. 8, T. 26N., R. 25E. A specimen collected 4 miles south of the Maxwell-Chico road on the east side of Chico Creek megascopically is greenish-gray and strikingly porphyritic with the feldspar phenocrysts, about 10 by 2–5 mm., equal to or slightly predominant over the fine-grained groundmass.

Tinguaite forms a dike in the creek bed where Chico road crosses Slagle Canyon; the dark-green rock is dense, with needle-like aegirine thickly disseminated throughout. Orthoclase, nepheline, and aegirine, and rarely mica make up the groundmass.

Localities: Melanocratic dikes.—A dark-gray, fine-grained to sugary rock from a dike south of Blosser Gap in Colfax County is an olivine basalt consisting of plagio-

clase laths, augite, olivine, and secondary carbonate. The rock has the same composition as the Clayton basalts and may be a feeder dike for Blosser Mesa, and thus belong to group A.

Two weathered and altered lamprophyres, very much alike, were collected on the Chico road on the west side of Slagle Canyon, Colfax County. One comes from the cut on the road (Pl. 4) and the other from a 2-foot dike cutting Timpas limestone. These rocks somewhat resemble minettes, and in hand specimen are light-brown, fine-grained rocks with fairly numerous flakes of biotite, 1–3 mm. across. The groundmass is composed of orthoclase laths, augite, and biotite. Mertie (Lee and Mertie, 1922, p. 12) has mentioned similar alteration in the lamprophyric dikes in the Raton-Brilliant-Koehler region, and says in describing sodic vogesites that "in addition to calcite and the chlorite and sericitic material developed in these rocks some quartz and zeolites are developed as secondary products." Magnetite and apatite are present as accessories. Biotite is not abundant enough to permit the name of minette, and therefore the name of vogesite has been given (Stobbe, 1949).

Other vogesite dikes are found in Colfax County in the area west of Slagle Canyon. One, an aphanitic, dark-gray rock weathering brown has orthoclase, plagioclase, hornblende, augite, and magnetite. The feldspar forms a ground for the ferromagnesian crystals, the hornblende is abundant in long, thin crystals; much magnetite and some secondary carbonate are present. Stobbe (1949) names it a hornblende-augite vogesite.

SUMMARY AND CONCLUSION

Northeastern New Mexico contains six extrusive igneous rocks groups which, from oldest to youngest are: (1) Raton basalts, fine-grained, olivine-bearing, uniform and normal basalts widely spread on high-level mesas along the northern part of the area, originally extruded chiefly from fissures on a low relief erosion plane and since etched into high relief by Quaternary stream action; (2) Red Mountain dacites, light-gray, fine-grained, hornblende dacites, in isolated medium-sized to large volcanic cones, now deeply dissected, found from Sierra Grande westward; (3) Slagle trachytes, fine-grained, porphyritic, soda trachytes in shallow sills, possibly flows in the southwest section; (4) Chico phonolites, greenish, fine-grained, commonly porphyritic phonolite flows and shallow sills forming mesas and uplands of moderate relief in the southwest section; (5) Clayton basalts, fine-grained to porphyritic olivine basalts emitted from fissures and cones at a lower erosion level than Raton flows, widely spread except in the northeast section, and etched into low to moderate mesa forms by stream erosion; the group includes a smaller amount of olivine-free and feldspathoid basalts and basanites; and (6) Capulin basalts, aphanitic, porphyritic, glassy, and scoriaceous olivine basalts extruded form isolated scoria cones and forming limited flows in present-day valleys, not eroded appreciably.

All the extrusive rocks are called Quaternary, chiefly because Ogallala sediments have been found beneath Raton (Mesa de Maya) basalts and Clayton basalts. Darton (1905, p. 178–179) and Lee and Mertie (1922, p. 8, 13) have reviewed much of the evidence, and nothing has been found to contradict their conclusions. Much Ogallala sand is found in the area but never on top of the Raton or Clayton basalt. The most

important positive evidence of Quaternary age found in the area is an exposure north of Clayton where soil and Ogallala sand pass under the Clayton basalt in a well-exposed contact.

The age sequence of the three basalt series is definitely established by physiographic and structural field evidence, as is the fact that the nonbasaltic group of dacite, trachyte, and phonolite rocks was erupted between the Raton and Clayton extrusions. More evidence is needed to give a positive sequence to the members of the nonbasaltic group. Probably the latest Capulin flows occurred within Recent or historical time.

Intrusive rocks appear to be most important in the Turkey Mountain and Palo Blanco domes. In the southwest quadrant, basaltic feeder dikes and leucocratic nonbasaltic dikes are known, and melanocratic dikes with E-W strike suggest a structural relationship with dikes 30 miles west.

The magmatic relationships of the igneous rocks of the area are treated more fully by Stobbe (1949). A single magmatic source is assumed; the three basaltic series agree well with this hypothesis, and the localized extrusion of nonbasaltic magmatic fractions during the middle life of the magma has numerous parallels elsewhere, although the details of magmatic development are problematical.

This paper, the first of a series on the geology of 4271 square miles of undescribed territory, is necessarily a preliminary description. A great deal of detailed work remains to be done; adequate maps are sorely needed; and more study of some key items is essential.

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PETROLOGY OF VOLCANIC ROCKS OF NORTHEASTERN NEW MEXICO

BY HELEN RUTH STOBBE

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ABSTRACT

The igneous rocks described in this paper were collected in an area about 86 by 50 miles in northern Union and eastern Colfax Counties, northeasternmost New Mexico. Lava-capped mesas and volcanic cones form prominent topographic features. The rocks are classified on a mineralogic basis. Basalts are the most widespread, dacites and andesites occur in subordinate amounts, and alkaline rocks such as phonolites and soda trachytes are localized in about 24 square miles in central eastern Colfax County. Petrology substantiates three main periods of basaltic extrusion which physiography indicates: Raton (earliest), Clayton (intermediate), and Capulin (recent). Olivine basalts predominate in all three periods and are

mineralogically similar with textural variations. Raton basalts are the most uniform in texture and mineralogy. Clayton flows are predominantly olivine basalts but include olivine basalts with quartz inclusions, analcime basanite, nepheline basalts, haüyne basalt, and olivine-free basalts. Red Mountain dacites have built volcanic cones and occur as plugs and necks. The alkaline suite is sodic. Chico phonolites occur as flows chiefly; Slagle trachytes associated with tinguaites and analcime microfoyaites occur in smaller amounts than the phonolites and are usually intrusives. The sodic rocks fall in line with the other alkaline groups which occur along the eastern front of the Rocky Mountains from British Columbia to Mexico. Dike rocks include leucocratic varieties such as hornblende dacite, phonolite, tinguaite, and analcime microfoyaite; and melanocratic varieties such as olivine basalt and lamprophyres (vogesite and monchiquite). The diverse rock types are believed to have originated from a parent olivine basalt magma.

INTRODUCTION AND ACKNOWLEDGMENTS

This paper is a companion paper to "Volcanic Rocks of Northeastern New Mexico," by Collins (1949). Although volcanic rocks in this area (Figs. 1, 2) have long been known, including a small group of alkaline rocks, no previous petrologic study has been made. St. John (1876, p. 283, 305–308), Stevenson (1881, p. 281), Hill (1892, p. 99), and Lee (1912, p. 357–365) briefly described some of the lava-capped mesas and volcanic peaks. The United States Geological Survey Folio, No. 214 (Lee and Mertie, 1922, p. 1–17) describes the geology of the Raton-Brilliant-Koehler Quadrangles just west of the region. The excellent petrographic descriptions in the folio have permitted a possible correlation of basalts in that region with those in this area. Collins' paper includes a geologic map and deals with the regional geology, geologic age, and areal distribution of the igneous rocks of northeastern New Mexico. This paper classifies the rocks and deals with their petrology.

The study has been based on Collins' collection of specimens and slides, supplemented by those of the late Samuel Prentiss Baldwin, who collected igneous rocks from northeastern New Mexico in 1893–1894 and turned them over to the United States Geological Survey. Thin sections of some of Baldwin's specimens were studied by government geologists including Whitman Cross. The writer visited the region especially the vicinity of Chico, during the summers of 1940 and 1948, and collected additional rocks for thin-section study. Over 400 specimens and slides were studied; they are believed typical of the different lavas and phases of volcanism present in northeastern New Mexico.

The several hundred square miles of lava flows and striking volcanic cones of this region are a portion of the extensive volcanic series along the Rocky Mountain front in western New Mexico, Arizona, and Colorado. The alkaline group lies within the belt (Fig. 3) which contains other alkaline flows and intrusives, small, isolated occurrences of which are known along the Rocky Mountain front from Ice River, British Columbia, to San José, Tamaulipas, Mexico. Rock types identified in this study include olivine basalts, olivine-free basalts, feldspathoid basalts, basanite, dacites, andesite, phonolites, tinguaites, soda trachytes, analcime microfoyaites, and lamprophyres (vogesites and monchiquite). This varied group, especially the alkaline series, presents an opportunity to study field and petrographic relations, and the possible origin of the rocks.

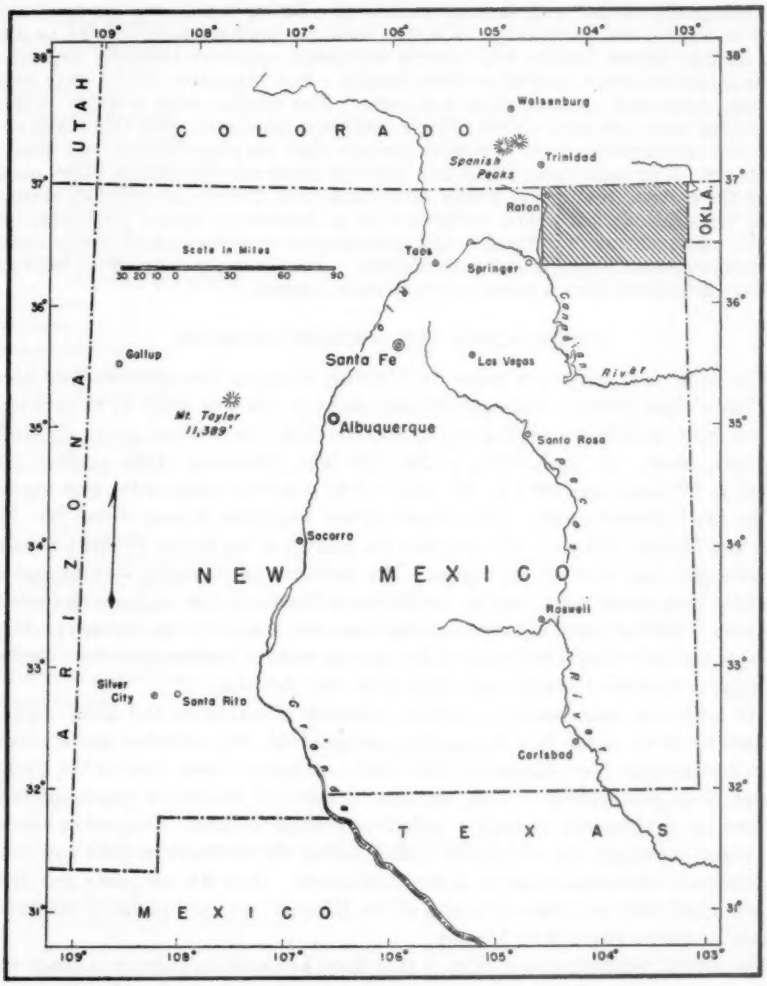

FIGURE. 1.—*Index map*

The writer wishes to thank those who assisted in the preparation of this paper. Professor R. F. Collins of Smith College made available his specimens, thin sections, and geologic map. He helped further in discussions and in taking the photomicrographs. Professor B. M. Shaub of Smith College took the following photomicrographs: Plate 2, figures 1, 2, 5, and 6 and Plate 3, figure 2. Mr. and Mrs. Roe Seward of Chico, New Mexico, are to be thanked for their hospitality during the writer's stay in the field. Miss Marie Bohrn of Mt. Holyoke College drafted the index maps. The petrologic work of this paper has been done under the direction of Professor S. J. Shand of Columbia University; it would be difficult for the writer to

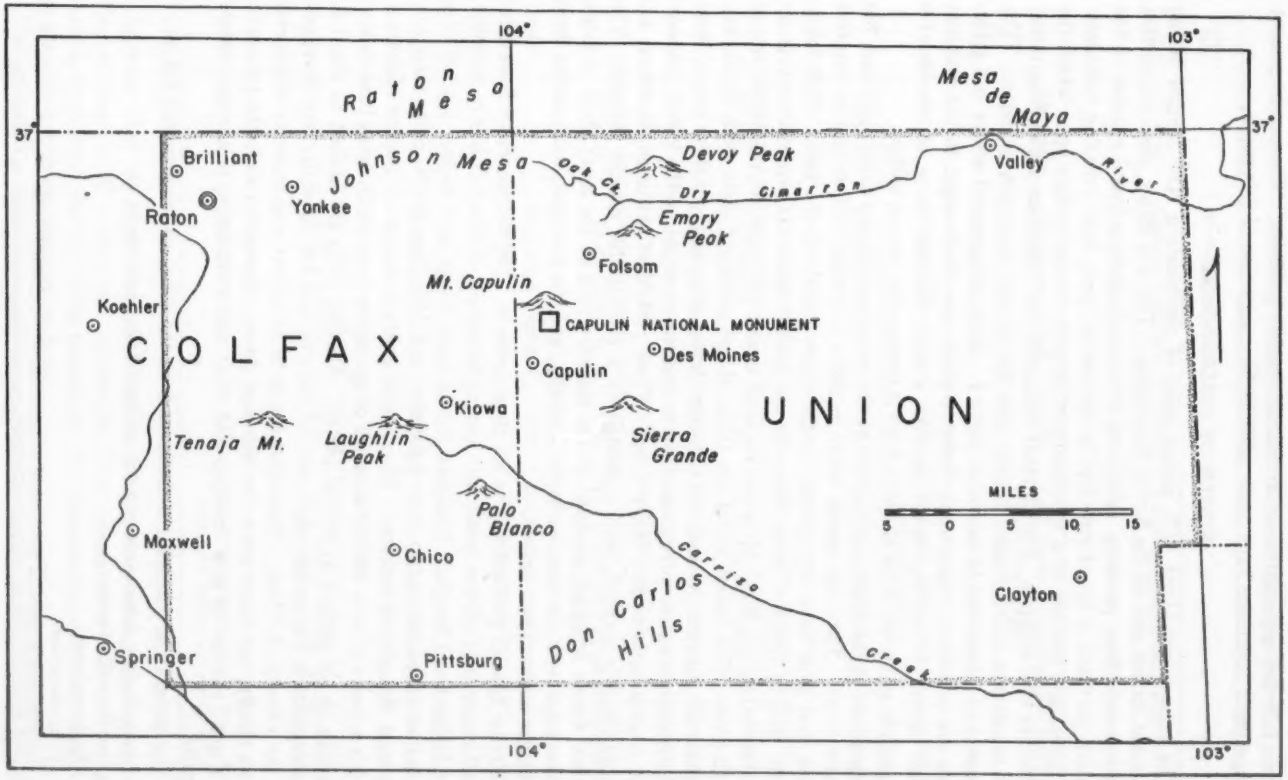

FIGURE 2.—*Location map of northeastern New Mexico*

express fully her appreciation of Dr. Shand's patient guidance. His encouragement and generous assistance have made possible the completion of this paper.

REVIEW OF COLLINS' WORK

The area covers about 4271 square miles of northeastern New Mexico in the piedmont section east of the Rocky Mountains. This is a highly dissected portion of the Great Plains province. Regional structure includes a broad syncline in the western part and a broad anticline in the central part, both trending northeast-southwest and beveled by a southeastward sloping erosion surface upon which the extrusives were erupted. Predominant sediments are Cretaceous shales, limestones, and sandstones which extend widely over the Rocky Mountain piedmont. The sequence of formations is shown in Table 1. High lava-capped mesas and tablelands are prominent topographic features which owe their origin to the resistant basalt cover. Other significant features include volcanic cones of considerable magnitude and lesser cones and lava flows in present-day stream valleys.

Basalts have the widest distribution of the volcanic rocks and cover more than 700 square miles. They cap mesas, occur as flows in stream valleys and as eruptive cones, and have three topographic levels, shown plainly in the field. High tablelands, such as Johnson Mesa, represent the highest level. Intermediate levels are represented such as Black Mesa and the large mesa which extends from Sierra Grande to Clayton. The lowest levels are those of the piedmont plain from which Mt. Capulin (Pl. 1.) rises. Nearly all the oldest lavas occur on the highest mesas, those of intermediate age at intermediate levels, and the youngest on the lowest, present-day, erosion surfaces and valley floors. Three periods of extrusion, therefore, are topographically marked, each separated by a considerable erosion interval. The earliest basalt flows are confined to the northern part of the area; those of intermediate age were the most widespread areally; and the youngest, most recent flows have the smallest areal extent.

Olivine basalts predominate in all three periods. The intermediate flows have small amounts of olivine basalt with quartz inclusions, olivine-free basalt, basanite, and feldspathoid basalts. Dacites occur as cones, plugs, and necks. No less than 12 extinct cones rise sharply from the surface and their clear profiles make them conspicuous topographic features. Hornblende andesite occurs on Turkey Mountain, which appears to be a shallow laccolith or apophysis from which lavas have broken through to the surface at several places. Alkaline rocks are limited to about 24 square miles in the southwestern part of the area, and are especially well developed in the vicinity of Chico. Phonolites are most abundant and occur as widespread flows chiefly, but there are a few sills and dikes. Associated with the phonolites is a small amount of soda trachyte and three minor intrusives of analcime microfoyaite.

The sequence of extrusion of the lavas from the oldest to the youngest follows:

Raton basalts: olivine basalts found on the highest topographic levels.
Red Mountain dacites
Slagle trachytes
Chico phonolites
Clayton basalts: basaltic rocks found at intermediate topographic levels.
Capulin basalts: olivine basalts found at the lowest topographic levels.

TABLE 1.—*Summary of sedimentary formations in northeastern New Mexico*
(Collins, 1949)

Quaternary		Unconsolidated gravels		
Tertiary	Pliocene	Ogallala formation	0–150	Yellow sand, some weak lime cement
	Eocene	Raton formation	1150	Buff sandstone, brown shale and coal seams
Upper Cretaceous	Montanan	Vermejo formation	0–200	Dark-brown to drab shale and buff sandstone, coal seams
		Trinidad sandstone	100	Massive light-gray medium sandstone
		Pierre shale	1800	Olive-gray shale, some lime at top and sand near bottom
	Niobrara	Apishapa shale	300	Limy shale, gray to tan. Some sandy layers
		Timpas limestone	50	Gray, impure, soft shaly limestone
	Benton	Carlile shale	150	Dark-gray limy shale
		Greenhorn limestone	50–80	Gray limestone and shale interbedded
		Graneros shale	150	Dark-gray shale
	Dakotan	Dakota sandstone	100	Tan to buff medium sandstone, massive and crossbedded
Lower Cretaceous		Purgatoire formation	150	Gray to buff massive sandstone overlain by thin dark shale
Jurassic		Morrison formation	150–300	Maroon to graygreen shales and sandstones interbedded, buff to brown sandstone
		Exeter sandstone	0–90	White sugary aeolian sandstone poorly cemented, massive crossbedded and lensy
Triassic		Dockum group	500+	Red sandstone and shale local white limestone lenses, some gray sand

Igneous dikes are grouped as (A) Basaltic feeders associated with Raton and Clayton basalts; (B) Leucocratic, nonbasaltic dikes associated with Red Mountain dacites, Slagle trachytes and Chico phonolites; (C) Melanocratic dikes not known to be associated with existing surface flows.

The geologic age of the lavas is given as Quaternary, that of the "basalts as Qua-

ternary, ranging from early Pleistocene to Recent." The evidence for a Quaternary age is the fact that the oldest basalt flows lie on the folded and beveled edges of the Eocene Raton formation. The most definite evidence observed is that "Ogallala sands of northern Union County, New Mexico, are never found on top of basalt flows, although they are in close approximation laterally".

STATEMENT OF PROBLEM

This study included a classification of rock types present in the area, a search for petrographic differences between the three main periods of basaltic eruption postulated from topographic and field evidence, a correlation with the basalt flows which adjoin the area to the west in the Raton-Brilliant-Koehler region, and a hypothesis as to origin of the different kinds of lavas erupted.

LABORATORY METHODS

Optical properties of minerals were obtained from thin-section and fragment studies. The liquid immersion method was used to obtain the indices of refraction recorded. All measurements for optic angles were made on the Fedoroff universal stage. Forty Rosiwal analyses were made with a Wentworth stage micrometer. One partial chemical analysis was made of a dacite, to determine whether this rock belonged to the andesite or dacite group, and an alkali determination was run on a specimen of microfoyaite. To prove the presence of feldspathoids, uncovered slides were made, treated with phosphoric acid, and immersed in methylene blue for one minute (Shand, 1939, p. 509). This stained all the feldspathoids, but the birefringence distinguishes nepheline from analcime.

CLASSIFICATION

The aim of any classification is to bring together like things. The rocks in northeastern New Mexico are effusives, save for minor intruded bodies. The classification used in this paper (Table 2) is a mineralogical one, following Shand (1943, p. 187–191), and is based upon the presence or absence of critical minerals such as quartz, olivine, and nepheline which represent either oversaturation or undersaturation of the magma with respect to silica, and indicate conditions in the cooling history and genesis of the magma with which we are dealing. These rocks can be further subdivided according to the kind of dark mineral present, which indicates whether there is an excess or deficiency of alumina present.

In dividing those rocks in which only saturated minerals are developed, Zirkel (1893, p. 834–835) has been followed; plagioclase-pyroxene rocks have been named olivine-free basalt, and plagioclase-hornblende rocks called andesite. The great majority of these lavas are olivine basalts, with a small number of feldspathoid, melanic rocks; there are fewer hornblende dacites and a small group of peralkaline rocks, chiefly phonolites. In the crystallizing of the magma, the pyrogenetic minerals olivine and pyroxene indicate crystallization from a hot, relatively anhydrous olivine basalt magma; with falling temperature and increasing water content hornblende andesite and dacites were formed. The minerals such as aegirine in the

phonolites indicate a late, low-temperature stage of crystallization from a soda-rich, residual alkaline magma.

Collins describes the areal geology of the Raton, Clayton, and Capulin basalts separately for his purpose but in the paper on the petrology, the similarity of the

TABLE 2.—*Tabulated classification of rocks*

Silica	Alumina		Rock types
I. Oversaturated	Metaluminous (some alumina in excess to enter dark minerals)		Hornblende dacites
II. Saturated	Metaluminous		Hornblende andesites
	Subaluminous (little or no excess of alumina to enter dark minerals)		Olivine-free basalts
	Peralkaline (alumina less than alkalies)		Soda trachytes
III. Undersaturated	Nonfeldspathoidal (deficiency of silica confined to dark minerals)	Subaluminous	Olivine basalts
	Feldspathoidal (alkalies partly or wholly unsaturated)	Subaluminous	Basanites and feldspathoid basalts
		Peralkaline	Phonolites Tinguaites Analcime microfoyaites

olivine basalts of the three periods would cause undesirable repetition. Therefore, in the section on the basaltic rocks, a mineralogic grouping has been followed. The olivine basalts of Collins' three eruptive periods, the Raton, Clayton, and Capulin basalts, are described together. The other basaltic rocks, all of which Collins has grouped as Clayton flows, are described separately. The order in which the non-basaltic rocks are discussed follows Collins.

BASALTIC ROCKS

Basaltic rocks include olivine basalt, olivine basalt with quartz inclusions, analcime basanite, nepheline basalt, haüyne basalt, and olivine-free basalt.

Petrology substantiates three volcanic periods indicated by topographic and eruptive evidence. Although olivine basalts predominate, the three groups show mineralogical and textural differences. The earliest flows show the greatest uniformity, are richest in olivine and poorest in large plagioclase crystals. The intermediate basalts are not uniform and in addition to olivine basalt, olivine basalt with quartz inclusions, feldspathoidal and olivine-free varieties occur. The most recent flows are characterized by microscopically prominent crystals in a poorly crystallized or glassy groundmass, which is typical of flows from volcanic vents. Furthermore, the latest basalts are poorer in plagioclase and olivine, and richer in pyroxene,

than the earlier flows. These differences do not mean that the olivine basalt lavas changed in composition, for chemical analyses (Lee and Mertie, 1922, p. 11) are quite uniform although olivine-free basalt (augite andesite of Mertie) and nepheline basalt of the intermediate period show differences. They must mean, therefore, different conditions of crystallization in the thinner, more quickly cooled recent lavas; and Mertie (Lee and Mertie, 1922, p. 11) suggests that the increase in the number of augite crystals may be "due to the greater power of spontaneous crystallization inherent in augite, than in plagioclase," and the large, intratelluric, feldspar crystals, he believes, "point to a longer period of cooling" before the latest lavas were extruded.

The chief difference among the olivine basalt lavas, then, is textural; progressive development of insets (phenocrysts) and change from coarser, fully crystallized to finer, more glassy types.

Evidence therefore shows that the volcanic cycle began with fissure eruptions of uniform olivine basalt. Eruptions from fissures and central vents produced the widespread, variable intermediate flows; and the latest period was characterized by thinner, texturally different flows, and by greater explosive activity.

OLIVINE BASALTS

GENERAL STATEMENT

The Raton basalts are confined to the northwestern part of the area near Raton and along the Colorado-New Mexico state line, eastward to Mesa de Maya. Specimens were examined from Johnson Mesa, the gap between Johnson and Hunter Mesas, Mesa Llargo, Hereford Park, the head of Oak Canyon, Devoy Peak, the Mesa north of Valley Post Office, Sec. 30, R.33 E, T.32 N, and other localities.

Clayton basalts cover the widest area and are distributed in the western and southern halves of the region. They show particular development between Des Moines and Clayton. Specimens were examined from: in the west, Yankee Volcano —the second outlier west, the gap between Hunter and Johnson Mesas, Blosser Mesa and Gap, Temples Peak, and Joe Cabin Arroyo; central region, Sierra Grande and the large, basalt-capped mesa which stretches from Sierra Grande to the town of Clayton; and northward in the Hereford Park section, Robinson and Burnt mountains, Emory Peak, and the volcano at the head of Brigg's Canyon.

The Capulin basalts cover the least area, spreading from western Union into central eastern Colfax County. They are volcanic cones of ash, cinders, and flows which continue far down valleys. Specimens from Horseshoe Crater , south cone of Twin Craters, and Mt. Capulin were examined.

MINERAL COMPOSITION

General Description. Olivine basalt is here used for dark, aphanitic rocks in which the alkalies are saturated and the deficiency in silica affects the dark minerals only. The color index[1] is always more than 30% (by volume) of dark or heavy minerals.

[1] "The ratio of heavy to light minerals is nearly the same as the ratio of dark-coloured to light-coloured minerals, and since it is this which mainly determines the colour of a rock it may be called the *colour ratio* or *colour index* of the rock. (The colour ratio of a rock is *x per cent*; its colour index is simply *x*.)" (Shand, 1943, p. 195–196.)

Plagioclase, pyroxene, olivine, and titano-magnetite compose these rocks in nearly constant proportions through the three eruptive periods. This shows clearly in the modes (Table 3). Apatite (less than 1%), present in nearly all the basalts, and a small amount of biotite in some of the earliest basalts are not included in the modes. Specimens Nos. 4 and 16 contain glass, and therefore the percentages of feldspar, pyroxene, and, in No. 16, magnetite also, were computed and added to the amounts measured; but these calculations do not affect the modes. Mineral averages (volume percentages), from Table 3, follow:

	Raton Basalts	Clayton Basalts	Capulin Basalts
Plagioclase	50	52	45
Pyroxene	28	26	32
Olivine	8	10	4
Magnetite	13	13	19

These figures show the Raton and Clayton basalts richer in feldspar and olivine, but poorer in pyroxene than the Capulin flows. These averages can, however, deviate. Specimen No. 2 (Table 3) coarser-grained than the typical early olivine basalts, gave 63.3% feldspar. To exclude this specimen brings the feldspar average down to 47%, which closely approximates 46%, given by Mertie (Lee and Mertie, 1922, p. 9) for corresponding olivine basalts in his area. For one of the Clayton basalts from Blosser Mesa, not averaged because not typical mineralogically, the Rosiwal analysis gave feldspar 67%, pyroxene 19%, magnetite 14%, olivine less than 1%, with a color index of 34. But olivine in the slide was confirmed with high power, and showed in crushed fragments. Furthermore, the feldspars, although more abundant were labradorite chiefly, like those in the olivine basalts. For these reasons, the rock was grouped with the olivine basalts.

Considering the hundreds of miles which these flows cover and their differences in thickness and crystallization, the modes are monotonously similar. Three chemical analyses (Lee and Mertie, 1922, p. 11), are given in Table 4. No analyses are available of Clayton olivine basalts, but their modes (Table 3) resemble the earlier and later flows.

As far as can be deduced from these 16 sections and Mertie's chemical analyses, the olivine basalt magma was similar in composition from earliest to recent flows.

Feldspar.—This is the most abundant mineral in the olivine basalts. It occurs in the groundmass as microlites and interstitial patches; as better developed and larger laths in some of the thicker flows; and as insets in the most recent flows. Carlsbad and albite twinning are common, pericline rare. When no albite lamellae are present, there is usually an undulatory extinction. Different growth forms have different compositions, which range from oligoclase ($\alpha=1.540$) to bytownite ($\gamma=1.576$), but labradorite (An_{50-60}) is the most common. The composition of the groundmass feldspars throughout the three eruptive periods remains the same.

Groundmass microlites (.05 – .5 mm) and small, albite-twinned laths are tabular with frayed ends. In composition they are sodic or andesine-labradorite (An_{50}) with extinction angle ($\perp 010)=28°$. Larger crystals without albite twinning are also labradorite (An_{55}; $\beta = 1.560$). Clear, untwinned, interstitial feldspar in the fine-grained basalts is oligoclase ($\alpha=1.540$; $\gamma=1.550$). In coarser-grained basalts

TABLE 3.—*Modes of basalts*
(Volume Percentages)
Olivine Basalts Nos. 1-9; 13-16a
Olivine-free Basalts Nos. 10-12

	Raton basalts						Clayton basalts							Capulin basalts				
	1	2	3	4	4a	5	6	7	8	9	10	11	12	13	14	15	16	16a
Plagioclase	57.8	63.3	48.7	43.6	27.0	37.9	61.7	48.6	47.6	49.3	57.5	60	35	40.3	52.3	42.4	42.0	34.3
Pyroxene	23.3	19.8	37.0	37.0	13.9	23.4	30.6	32.0	18.9	22.0	21.8	30	22	31.2	30.3	35.2	32.7	4.6
Olivine	6.6	13.5	4.1	6.8	6.8	11.9	1.8	7.4	13.6	9.8	—	—	—	3.9	3.0	2.9	8.3	8.3
Metallics	12.3	3.4	10.2	12.6	12.6	26.8	5.9	12.0	19.9	18.9	20.7	9	8	24.6	14.4	19.5	17.0	—
Glass	—	—	—	—	39.7	—	—	—	—	—	—	—	35	—	—	—	—	52.8
Color Index*	(42)	(37)	(51)	(56)	(33)	(62)	(38)	(51)	(52)	(51)	(42)	(39)	(30)	(60)	(48)	(58)	(58)	(66)

1. West edge of Johnson Mesa.
2. Mesa north of Valley Post Office.
3. East end of Johnson Mesa.
4. North edge of Johnson Mesa (feldspar and pyroxene partly calculated).
4a. North edge of Johnson Mesa (same slide, but minerals as measured).
5. Devoy Peak, north of Folsom.
6. Flow from Sierra Grande to Clayton, 4 miles due east of Clayton.
7. Same flow, 7 miles west of Clayton.
8. Two miles east of Green Mountain.
9. South side of Joe Cabin Arroyo.
10. Mesa east of Meloche Mesa.
11. Mesa east of Meloche Mesa (augite andesite of Mertie, 1922, p. 10).
12. West base of Sierra Grande.
13. Top of south Crater of Twin Craters.
14. Flow from Capulin, 1 mile north of Stuyvesant Place.
15. West base of Capulin.
16. End of Capulin flow down Dry Cimarron Valley (feldspar, pyroxene, magnetite calculated).
16a. Same as 16 but minerals as measured.

* See footnote 1.

TABLE 4.—*Analyses and norms of basalt lavas from the Raton Mesa region, New Mexico*
(U. S. Geol. Survey Folio, 214, p. 11., George Steiger, analyst)

Analyses

	1	2	3
SiO_2	51.68	49.73	53.27
Al_2O_3	15.05	15.46	15.43
Fe_2O_3	5.22	3.32	2.43
FeO	5.64	8.14	6.50
MgO	5.63	7.20	6.16
CaO	8.30	9.63	8.18
Na_2O	3.75	3.30	3.51
K_2O	1.39	.87	1.71
H_2O-	.72	.16	None
H_2O+	.62	.32	.62
TiO_2	1.54	1.59	1.30
CO_2	None	None	None
P_2O_5	.45	.42	.50
S	—	—	—
MnO	.12	.13	.12
	100.11	100.27	99.73

Norms

	1	2	3
Quartz	1.56	—	1.14
Orthoclase	8.34	5.00	10.01
Albite	31.96	27.77	29.34
Anorthite	20.02	25.02	21.41
Corundum	—	—	—
Leucite	—	—	—
Nepheline	—	—	—
Diopside	14.71	16.01	12.61
Hypersthene	10.84	9.50	17.34
Olivine	—	7.62	—
Hematite	—	—	—
Magnetite	7.66	4.87	3.48
Ilmenite	2.89	3.04	2.43
Apatite	1.01	1.01	1.34

1. Olivine basalt. First eruptive period.* East rim of Barilla Mesa, near Yankee, N. Mex. Symbol, II (III).5.3.4. Andose.

2. Olivine basalt. Second eruptive period.* South rim of Barilla Mesa, at the mouth of Chicorica Creek, Colfax County, N. Mex. Symbol, ^{1}III 5.3^{4}4(5). Camptonose.

3. Olivine basalt. Fourth eruptive period.† Mount Capulin, Union County, N. Mex. Symbol, II(III).5.3.4. Andose.

* First and second eruptive periods of Mertie are equivalent to Raton basalts in this paper.

† Capulin basalts of this paper.

(.7 mm), where feldspars crystallized more slowly, labradorite is more calcic (An_{70}), as shown by extinction angle = 30° on combined Carlsbad and albite twins. This kind of feldspar is found in the thick Clayton basalts which cap the mesa from Sierra Grande to Clayton. Feldspars in the coarsest Raton basalts approximate this compo-

sition, with extinction angle ($\perp$ 010) = 43°, thus indicating a calcic labradorite or bytownite composition. One crystal, measured on the universal stage, gave An_{68} according to Reinhard's chart, with 2V (Z) = 84°, and Manebach-acline or ala twins.

Insets are labradorite (mean index = 1.564). The largest crystals (2 mm) show cores of bytownite (γ = 1.576) and more sodic rims. Fringed borders are andesine-labradorite (An_{50}) with extinction angle ($\perp$010) = 28°. The borders are sometimes clear with oscillatory extinction and invariably have ragged edges. Groundmass inclusions riddle the interiors, sometimes in cuneiform patterns. An occasional large crystal which appears uniform in plane light reveals under crossed nicols several feldspars grown together. Intratelluric insets in volcanic lavas commonly change composition from core to rim. Either residual lava, becoming more sodic as crystallization proceeds, reacted with the early formed calcic core, so that the crystal became sodic in the outer portions; or extravasation suddenly interrupted the growth of the original crystal, and the borders are later feldspar added as the more sodic residuum solidified. Further evidences of magmatic reaction are indistinct twinning and serrate edges.

Pyroxene. A clinopyroxene, augite, the second most abundant mineral in the basalts, has grown as groundmass prisms, insets, and interstitial granules between feldspar laths in the coarser crystallized basalts. Groundmass pyroxenes are colorless to pale green, faintly pleochroic, prismatic crystals (.05–.1 mm). The insets (1 mm diameter) occur singly or in clusters, are greenish-yellow or colorless to tan, often with tan borders and colorless to gray cores. Usually they make clean-cut contacts with the groundmass, and only an occasional larger crystal shows resorption or border inclusions. Nearly every crystal shows either border or hour-glass zone structure. Crystals have inclusions of groundmass, magnetite, and sometimes olivine. Augite of the coarser-grained basalts is tan, and occurs both as idiomorphic crystals and granules interstitial to feldspar. In general, these different forms show no marked differences, for optical properties are much alike: Bx_a = Z; 2V = about 60°; Z$\wedge$ c = 49°. The mineral is always optically positive, and the figures for 2V are averages of readings on the universal stage, made on a number of typical slides from rocks of the three eruptive periods. Groundmass pyroxenes in fine-grained basalts have an average 2V = 59°, Z$\wedge$c = 48°; in coarse-grained rocks 2V = 62°, Z$\wedge$c = 48°; and insets have 2V = 63°, Z$\wedge$c = 50°. 2V in groundmass crystals ranged from 52°–66°, and Z$\wedge$c from 43°–53° with 48° the most frequent highest angle. Optic angle readings for insets spread from 61°–67° but 62° was a common figure with a sodium vapor lamp; while Z$\wedge$c = 46°–54°, averaged 48° for the earlier basalts and close to 50° in the recent flows. These measurements for groundmass and inset pyroxenes show that with increase in the optic angle, the extinction angle between Z and c also rises, thus signifying a slight composition change which zoned insets corroborate, for their cores give higher extinction values than rims and groundmass crystals. It is not unusual for rims and groundmass to be close in composition, for a continuous reaction exists between the crystals and residual lava. The differences in the pyroxenes are small, for the readings found, because high 2V values (about 60°) came from both groundmass and inset crystals, but 2V extended to lower values (52°) in the groundmass crystals. It must be remembered that these insets

are microscopic, and may not be intratelluric, for usually their edges are not corroded; they therefore may have formed only slightly before, during, or after extrusion, and for this reason not differ greatly in composition from groundmass crystals. In larger insets, however, whose edges do show corrosion the colorless cores may be richer in lime that the borders. Optical properties for two augites (Larsen and Berman, 1934, p. 130, 128) show twice as much CaO in the mineral with higher optic and extinction angles as follows:

Augite	Augite
2V = 65°–67°	2V = 60°
Z ∧ c = 46°–51°	Z ∧ c = 48°
(CaO—23.56%	(CaO—11.4%)
(MgO—11.29%	(MgO—13.3%)

The optic angle of the New Mexican pyroxenes is near 60° and Z∧c = 48°, indicating an ordinary augite, perhaps with about equal amounts of CaO and MgO if one considers the analysis from Larsen and Berman (1934, p. 128).

Barth (1931, p. 196, 208) has found the low-angle pyroxene, pigeonite, "the most abundant pyroxene in volcanic rocks," and gives 2V = 0°–50° for groundmass crystals in the Pacific lavas. No low-angle pyroxenes were found in the New Mexican basalts, but further search may reval them. Hess (1941, p. 525) writes that augite accompanies pigeonite "in most if not all natural occurrences"; he believes (1944, p. 625) that the commonest clinopyroxene of basalts has an optic angle about 45°. On the other hand, Macdonald (1944, p. 628) found 2V = 0°–50° in the Hawaiian and Samoan basalts, and reports (Stearns and Macdonald, 1942, p. 295) 2V = 60° in the lavas of East Maui, Hawaii.

Pyroxene insets are of two kinds. Rarer and larger intratelluric crystals, more poikilitic with zoned, irregular, and corroded borders give higher value for the optic angle and Z∧c; and hence should be richer in lime. Smaller insets which may have crystallized not long before or after extrusion have sharp groundmass contacts and slightly lower optical values suggestive of less lime. This evidence shows that crystallization has proceeded from lime-rich to lime-poor pyroxenses.

Olivine.—Olivine averages 8% in the basalts. Glassy, green insets, sparse in hand specimens, show under the microscope as euhedral crystals, 1–2 mm. long, elongated parallel to the c-axis, with well developed pinacoids and domes. Crystals grew singly or in groups. Smaller (.2 mm.) granules are scattered throughout the groundmass. Optical tests show a magnesia-rich variety (index > 1.649 < 1.719); Bx_a = Z; 2V = 88° and Bx_a = X; 2V = about 85°. The olivine in all three flows was tested by obtaining the sign on optic axis figures with the microscope, and by the use of the universal stage. The optic angle varied from close to 90° positive to 84° negative, and a negative 82° reading was obtained from olivine in one of the Raton and one of the Capulin basalts.

Following Winchell's chart (1933, p. 191), the olivine holds 8%–19% fayalite (molecular percentage), as the angle varies from positive 2V = 88° to negative 85°. Lower optic angle values (2V = 82°) would hold more fayalite (28% of $FeSiO_3$). Cores of insets (+2V = 88°) carry more magnesia than borders. Smaller and fewer olivines are found in the Capulin flows and more grains gave negative signs,

indicating more fayalite than in the earlier olivines. This, however, does not appear in Mertie's chemical analysis (Table 4), so that any difference in olivine may be too small to have significance. The change in MgO and FeO here encountered suggests a close parallel to trends of differentiation in the Hawaiian Island olivines (Stearns and Macdonald, 1942, p. 314).

Mertie (Lee and Mertie, 1922, p. 9, 11) found iddingsite abundant enough to use as a criterion to distinguish periods of flow. He says the alteration of olivine to iddingsite is general, but has not progressed so far in the later flows as in the earliest basalts. Most olivines in the New Mexican basalts examined by the writer are fresh, but iddingsite and serpentine do occur and may have resulted from hot, late-stage solutions. Red specks (1–2 mm.) of iddingsite occur rarely in hand specimens. When seen microscopically, the bright-red mineral replaces small olivines and forms rims around larger ones, forming prominent pseudomorphs in a few basalts only (Pl. 2, fig. 1). As such it was found in the Raton basalts at Devoy Peak and the mesa north of Valley Post Office; in the Clayton flows at Joe Cabin Arroyo and the mesa from Sierra Grande to Clayton; but there was only a suggestion of its presence in the Capulin basalts. A serpentine (antigorite)-chlorite-limonite mixture replaces olivine in two specimens of Raton basalts, one from Hereford Park and the other from the gap between Johnson and Hunter Mesas.

Metallics.—The basalts contain between 4% and 26% of metallics, probably titanomagnetite. Uniformly scattered, equant grains form part of the groundmass, especially in the more evenly crystallized basalts. An earlier generation of larger, irregular patches and octahedra occur, and various sized grains are enclosed in olivine and pyroxene and, together with groundmass particles, riddle the inner portions of the larger pyroxenes. Magnetite dust imparts a black color to the glassy matrix of some basalts, such as that on Mesa Llargo, and bombs from Mount Capulin. The groundmass of these rocks appears as a black glass, but a high power lens shows individual grains of magnetite. This abundant magnetite probably furnished the red, ferric iron coat on recent bombs and scoriaceous lavas.

Apatite and Biotite.—Apatite (1%) occurs in nearly all the basalts, especially the holocrystalline ones. It forms very slender, colorless, needle-like crystals, with low birefringence, and is best seen with a high power lens. A little pleochroic tan to brown biotite occurs in some of the Raton flows.

TEXTURE

Olivine basalts have textures from dense to vesicular and scoriaceous. Typical Raton and Clayton flows are medium to dark gray, vesicular to compact rocks with vesicles (2 mm. rarely 5 mm.), and olivine crystals (2 mm. long). Sometimes calcite fills vesicles. Capulin basalts are more scoriaceous, probably because of the relative thinness of the flows charged with escaping volatiles, and also because the increased explosive activity produced tuffs and breccias in larger quantity than in the earlier periods. Microscopically, these basalts present many structures from holocrystalline to more than 50% glassy. Flow structure shows prominently, especially about vesicles and insets. All rocks are microporphyritic but in varying degrees, some with a few insets, others with groundmass and insets about equal. In the thickest flows

the texture coarsens, with interlacing feldspar laths (.7 mm.) and pyroxenes interstitial. The size of the groundmass feldspar, pyroxene, and magnetite, averages .05–.1 mm. and the feldspar laths are often matted or felted into a pilotaxitic structure in the holocrystalline rocks. Olivine, pyroxene, and feldspar form insets (2 mm.), olivine alone in the earliest flows followed by a progressive tendency for pyroxene and feldspar to form large crystals in the later flows. Striking feldspar microinsets characterize the latest basalts.

Different textures, in some cases, mark the eruptive periods. The Raton flows generally are holocrystalline and uniform in texture, only sparsely porphyritic with olivine insets (Pl. 2, fig. 2). They are fine-grained (.05–.1 mm.) with one coarse-grained (.7 mm.) representative (Pl. 2, fig. 3) from the mesa north of Valley Post Office, which adjoins the thick flows of the high mesa region of southeastern Colorado. These basalts correspond to the "first period of eruption" which Mertie (Lee and Mertie, 1922, p. 9) describes in the Raton-Brilliant area. Not all early flows crystallized fully. The lava from Mesa Llargo has a black, glassy groundmass, and the basalts from the north and east ends of Johnson Mesa have purplish-brown glass (39%), small feldspar crystals and insets (50%) of olivine and pyroxene. These rocks give evidence of sudden chilling and quick cooling on the surface or bottom of flows. Two textural types can be distinguished in these early flows: fine- to coarse-grained, holocrystalline, with sparse olivine insets, and hypocrystalline with pyroxene and olivine insets. The former corresponds to the first period of eruption (Qb^1) in the Raton-Brilliant region; and the latter to the second period (Qb^2).

The Clayton basalts, with feldspar insets, present the greatest range of textures. Many flows are holocrystalline with olivine insets alone, and these hardly differ from the early flows. Others range from partly glassy to coarsely crystalline rocks; insets and clusters of pyroxene are common, and single feldspar insets which are uncorroded, and smaller than the distinctive, poikilitic insets of the Recent basalts. Most of the basalts of this eruptive period were flows, but vitrophyric scoria from the vicinity of Burnt Mountain and breccia from the volcano at the head of Brigg's Canyon, indicate explosive activity.

The Capulin basalts differ in texture from the rocks of the two earlier periods because their chief occurrence is on cinder cones and as thin flows; hence a glassy matrix, bombs, scoria, and breccia dominate. Capulin best exhibits these textural varieties. Some rocks are holocrystalline, others contain as much as 40% black glass (Table 3, no. 16a), as in the basalt from the end of the flow from Capulin Mountain down Dry Cimarron Valley (Pl. 2, fig. 4). Holocrystalline olivine basalt and scoriaceous bombs both come from Capulin Crater (pl. 1, fig. 2). The holocrystalline basalt is like the other fully crystallized rocks with a groundmass of feldspar laths, pyroxene crystals, olivine and magnetite granules, and insets of olivine, pyroxene, and feldspar. Three generations of feldspar are distinguishable; groundmass microlites (.05 mm.), lath-shaped crystals (.1 mm. wide and .5 mm. long) scattered as insets, and occasional striking insets (2 mm. long and .5 mm. wide) which belong to the earliest generation. The largest insets (Pl. 2, fig. 5) occur sparingly, their contacts with the groundmass are uneven with irregular groundmass aggregates projecting into the crystals. Inclusions of ground mass riddle the interiors, sometimes

in cuneiform patterns. As a contrast to this rock, the bomb from the west side of the crater rim shows a coarse, vesicular structure with numerous blowholes. Microscopically, the glassy base is dusted with black magnetite particles. Plagioclase and pyroxene form insets, and rare olivine (.1 mm.) occurs. Similar hyalocrystalline olivine basalts come from Horseshoe and south cone of Twin Craters. Pyroclastics of volcanic ash and breccia also occur on Capulin, and are described below in the section on pyroclastics. The Capulin basalts differ from the earlier flows by having additional glass, thus a poorer degree of crystallization, and by yielding a larger quantity of pyroclastics. Feldspar insets with riddled interiors, either clear or albite-twinned rims, and ragged edges are a striking feature. They typify these flows, and no doubt are intratelluric, having formed in the magma chamber or volcanic conduit before eruption.

PYROCLASTICS

A basalt breccia was erupted during the intermediate period from the top of the volcano, at the head of Brigg's Canyon, northeast of Folsom, Union County. A hand specimen consists of fragments of basalt, sandstone, and a fine-grained whitish rock. Microscopically, the angular pieces show as scoria (2 mm.), trachyte (?), and quartz grains. The scoria consists chiefly of a colorless glass, impregnated with abundant magnetite and a few minute feldspars, with the larger ferromagnesian minerals altered to magnetite or limonitic aggregates. The trachyte consists of rosettes of feldspar, with an altered dark mineral here and there. Angular and rounded quartz grains (.5 mm.) vary in abundance. They probably belonged to a sandstone, broken and incorporated in the lava.

Pyroclastics of recent eruptions, primarily from Mount Capulin, were examined. This mountain erupted ash, lapilli, cinders, and bombs. A buff-colored volcanic ash, with vesicular basalt fragments (5 mm.), occurs on the west bank of the road, 3 miles north of Folsom. Microscopically, fragments consist of basaltic glass and limestone. The olivine basalt glass is opaque with thin brown edges, and has incorporated limestone, now in circular or elongate fragments, which show a bit of shaly cement, and compose about 50% of the slides. Basaltic bombs with sandstone inclusions occur commonly. Under the microscope they are light-tan glass or black, basaltic glass with corroded feldspar fragments and altered pyroxene and olivines. Corroded quartz grains of the sandstone have irregular and embayed edges, and small pyroxenes have crystallized as reaction rims about their edges. These specimens show that the lava has come through limestone and sandstone on its way to the surface.

OLIVINE BASALTS WITH QUARTZ INCLUSIONS

Quartz inclusions occur in olivine basalts from Yankee Volcano and Emory Peak. One specimen, a nepheline basalt, is described in the section on feldspathoid basalts. Yankee Volcano is situated in the valley northwest of Johnson Mesa, and two outliers of lava are preserved which flowed west from it. Olivine basalt from the top of the lava cap of the second outlier west, is a medium- or lead-gray, fine-grained, vesicular basalt. Microscopically, it is like the other holocrystalline, microporphy-

ritic olivine basalts, which contain labradorite, augite, magnetite, and olivine in a fine-grained (.05–.1 mm.), matted groundmass with euhedral pyroxene and olivine insets. This basalt belongs to the Clayton flows, and differs from the typical olivine basalts only because it carries quartz inclusions. The quartzes occur sparingly (.5%), and are as large as 1.5 mm in grain size. They lack crystal form, have been cracked internally, and magmatic corrosion has rounded and embayed their edges. Reaction rims border the grains, and have progressed further than the incipient pyroxene rims about the sandstone grains in the basaltic bomb. Reaction between magma and quartz has resulted in some cases, in a pale, lucid glass rim between quartz and augite crystals. The augites border the crystal, and are arranged radially with respect to the center. Different stages of resorption show, and when magma and quartz have completed reaction, a group of augite crystals, with their terminations pointed toward the center, takes the place of the quartz. The most beautiful and perfect example is in the Emory Peak olivine basalt, where a quartz eye is entirely surrounded by a wide, radiating outward halo of augite crystals. These slides compared with several quartz basalts from Cinder Cone, Lassen Peak, California, showed that the quartz grains and reaction rims in both appear alike.

Quartz inclusions in basalt, no longer considered unusual, have been reported from a number of localities in the southwest—Eureka, Nevada (Hague, 1883, p. 279–280); Santa Maria Basin, Arizona (Iddings, 1888, p. 211; 1890, p. 21); Anita Peak, 15 miles northeast of Hayden, Colorado (Iddings, 1888, p. 212; 1890, p. 22); Mounts Trumbull and Logan, Grand Canyon region, Arizona (Diller, 1891, p. 31). Diller also describes them from the volcanic necks east of Mt. Taylor, New Mexico, and comments that the great majority of basalts of that region, all of which have passed through the same formations on their way to the surface, show no trace of quartz; but that those from the volcanic necks show "eyes of pyroxene with here and there a trace of phenocrystic quartz." In north-central New Mexico, quartz basalts from the Tewan Mountains, vicinity of the Rio Grande Canyon, have been described (Iddings, 1888, p. 208–221; 1890, p. 9–34).

The origin of quartz in mafic lavas puzzled the older geologists, who considered it primary as Diller (1891, p. 28) considered the quartz in the basalt of Cinder Cone, Lassen Peak. Finch and Anderson (1930, p. 271–73) have since shown that the quartz in the Lassen Peak basalt comes from "acidic xenoliths and xenocrysts derived from a differentiated dacitic magma." The quartz in the Tewan Mountains, north-central New Mexico, Iddings (1888, p. 221; 1890, p. 31) believed to be primary, even though chemical analyses showed the basalts to be normal and the presence of quartz therefore not determined by the chemical composition of the magma. Mertie (Lee and Mertie, 1922, p. 10) describes the Yankee Volcano quartz basalt, but does not discuss its origin. Each specimen carries a small amount of quartz, but otherwise is a normal olivine basalt. The quartz could have come from underlying sandstone. Glass and augite rims further indicate a foreign origin for the quartz. Had there been any excess of primary silica in the nepheline basalt it would have formed feldspar, and been completely used up, for the nepheline rock is undersaturated with respect to silica. The evidence points, therefore, to a foreign origin for the quartz; and although the rock can be called quartz olivine basalt, olivine basalt with quartz inclusions denotes its character more truly.

TABLE 5.—*Modes of analcime basanite and feldspathoid basalts*
(Volume Percentages)

Minerals	1 Analcime basanite	2 Nepheline basalt with quartz inclusions	3 Nepheline basalt of Mertie	4 Nepheline basalt	5 Nepheline basalt (Utah)	6 Nepheline basalt (Idaho)	7 Haüyne basalt	8 Haüyne basalt of Mertie
Nepheline	—	14.7	11	20.4	15	20	4.6	3
Haüyne	—	—	—	6.1	—	—	9.2	5
Analcime	17.2	—	—	—	3 (from nepheline)	—	—	—
Plagioclase	20.6	8.8	—	—	—	—	7.9	8
Pyroxene	37.8	51.6	61	40.7	40	39	46.3	61
Olivine	19.1	10.4	10	2.7	20	26	9.5	10
Magnetite	5.3	13.4	8	25.0	2.0 (includes apatite)	3	12.5	13
Biotite	.1	—	—	—	20	8	—	—
Quartz	—	.3	—	—	—	—	—	—
Glass	—	.8	10	2.1	—	—	—	—
Carbonate	—	—	—	3.0	—	—	—	—
Rest						4		
Color Index*	(75)	(75)	(79)	(68)	(82)	(76)	(68)	(84)

1. Knoll northeast of Pittsburgh, Colfax County.
2. Second outlier west of Yankee Volcano.
3. Yankee Volcano (Lee and Mertie, 1922, p. 10).
4. Robinson's Peak.
5. Stockton, Utah (Gilluly, 1932, p. 62–63).
6. Fort Hall Reservation, Idaho (Mansfield and Larsen, 1915, p. 468).
7. Low hill at north end of Hunter mesa, in the saddle between Johnson and Hunter mesas.
8. Saddle at north end of Hunter mesa (Lee and Mertie, 1922, p. 10).

* See footnote 1.

BASANITES AND FELDSPATHOID BASALTS

GENERAL STATEMENT

Highly melanocratic, olivine-bearing rocks, undersaturated in silica, form a part of the Clayton eruptive series. Although they occur in limited areas, compared to the hundreds of square miles covered by ordinary olivine basalts, they lend variety and interest. Grouped in this section of melanic feldspathoid rocks are all the dark, fine-grained olivine rocks which bear feldspathoids. Plagioclase feldspar just slightly exceeds feldspathoid in an analcime basanite; but is absent or accessory in the nepheline basalts and haüyne basalts. One of the nepheline basalts carries quartz inclusions. All of these rocks contain pyroxene, olivine, and magnetite, and the color indeces (Table 5) range from 68 to 75.

Nepheline basalt with quartz inclusions comes from the Yankee Volcano flow, north of the western end of Johnson Mesa. Haüyne basalt with nepheline is found in the saddle between Johnson and Hunter Mesas. Nepheline basalt with haüyne occurs on Robinson's Mountain 7 miles southwest of Folsom or about an equal distance northwest of Sierra Grande. Sierra Grande and Emory Peak, the former

south and the latter east of Folsom, also have melanocratic, feldspathoidal rocks. The analcime basanite described was found in the southwestern part of the area, at Pittsburgh south of Chico. Feldspathoid basalts are also known in the south-central region, in the Don Carlos Hills.

Hand specimens are black, fine-grained, vesicular or compact rocks. Porphyritic textures were noted in thin sections. Modes in Table 5 show the following proportions: nepheline (4%–20%), haüyne (6%–9%), analcime (17%), feldspar (0%–20%), pyroxene (37%–51%), olivine (3%–19%), magnetite (5%–25%).

These rocks have textural peculiarities. The nepheline basalt with quartz inclusions so closely resembles other olvine basalts, that one could only suspect nepheline until the blue stain showed its presence. In some of the rocks where nepheline and haüyne are associated, nepheline is interstitial in the groundmass and haüyne forms distinct microinsets. The most unusual nepheline basalt is one which has irregularly shaped vesicles filled with nepheline, glass and pyroxene. The analcime basanite has a coarser texture, and analcime ocelli characterize it. Separate descriptions follow because of the individuality of these rocks.

ANALCIME BASANITE

A small knoll of analcime basanite occurs in the southwestern part of the area, 2 miles northeast of Pittsburgh, Colfax County, in the western half of section 36, R. 26 E., T. 25 N.

Hand specimens are melanocratic, aphanitic rocks which weather with a pimply surface. Microscopically, the rock is holocrystalline, coarser-grained (.5 mm.) than the feldspathoid basalts and has a sugary, panidiomorphic texture and prominent analcime ocelli. The mode is given in Table 5, no. 1. Feldspar is clear and twinned according to Carlsbad and albite laws. Untwinned feldspars are interstitial. Twinned laths (.5 by .05 mm.), matted, are labradorite with extinction angle ($\perp 010$) = 35° and approximate composition An_{6}. Pyroxene is a tan, pinkish-lavender titan-augite ($+2V = 60°$) with low, sometimes anomalous blue, interference colors, and zones which do not extinguish homogeneously for in cores $Z \wedge c = 48°$, intermediate borders = 42°, outermost rims 51°, thus indicating an increase in oxides of titanium, aluminum, and ferric iron in the outer zone (Winchell, 1933, p. 230). Many crystals carry magnetite inclusions. Olivine occurs in colorless, euhedral insets (1.5 mm.) with $(+)\ 2V = 86°$. Magnetite, in smaller quantity than in other basalts, is scattered throughout in squares, octahedra, and irregular patches as well as inclusions in pyroxenes and olivines. A few flakes of tan-yellow-brown biotite and small hexagons and prisms of apatite also occur.

The unusual feature of this rock is the ocellar texture. Oval, analcime ocelli, often with analcime stringers connecting them, stand out with high relief because of the lower index of the analcime, and pale pinkish lucid quality. Generally isotropic, it sometimes shows anomalous birefringence. Prismatic augite crystals lie with their long axes tangential to the periphery of analcimes. Scattered throughout the groundmass of the rock are triangular, interstitial, isotropic analcime patches. These ocelli appear to be miarolitic steam or gas cavities, filled with the latest minerals to crystallize from the magma.

NEPHELINE BASALTS

Nepheline basalt with quartz inclusions comes from the second outlier west of Yankee Volcano, the same locality which yielded olivine basalt with quartz. Megascopically, the rock is a medium-gray, fine-grained vesicular basalt. Microscopically, it is essentially holocrystalline, and composed of nepheline, plagioclase, pyroxene, olivine, magnetite, quartz inclusions, and glass of reaction rims. A small amount of colorless, isotropic glass may be interstitial in the groundmass. Nepheline is the dominant salic mineral, feldspar (< 10%) subordinate. Nepheline, with low birefringence, is interstitial between other groundmass minerals. Labradorite occurs in small laths, and also an untwinned, interstitial feldspar. Pyroxene and olivine have the same textural habits as in the olivine basalts. Olivine is optically negative, 2V about 85°. Nepheline basalt from Yankee Volcano, described by Mertie (Lee and Mertie, 1922, p. 10), has anhedral nepheline in the groundmass, and lacks feldspar. Mertie does not mention quartz. Proportions of nepheline and feldspar often vary in feldspathoid basaltic rocks, and some specimens may have nepheline low or absent. Furthermore, it is difficult to distinguish between the two minerals, until the methylene blue stain brings out the nepheline. Mertie's mode (Rosiwal analysis) follows: augite (61%), nepheline (11%), magnetite (8%), olivine (10%), glass (10%); a chemical analysis (Lee and Mertie, 1922, p. 11) shows a considerably lower SiO_2 content (40.7%) than found in normal olivine basalts (50%). Mertie's mode (Table 5) differs from the mode of the specimen examined chiefly by its lack of feldspar and higher percentage of glass. Scarce quartz inclusions, believed to be of foreign origin (Pl. 2, fig. 6), have glass and augite reaction rims, like those in the olivine basalt. Lacroix (1893, p. 17–48) cites examples, expecially European, of olivine basalts and nephelinites with quartz inclusions enclosed by glass and augite rims.

The writer's specimen from Yankee Volcano could be classified as a nepheline basanite, because this name is widely used for nepheline-bearing olivine basalts which have dominant or accessory feldspar. A basanite is recorded from Ciruella, Colfax County, New Mexico. A chemical analysis is given by Clarke (1900, p. 171) and Washington (1917, p. 677); and a brief petrographic description of the rock by Cross accompanies the analysis in Clarke. The rock "contains augite, olivine, nepheline, plagioclase, magnetite, apatite, and a little biotite," and is named a nepheline basanite.

A true nepheline basalt without feldspar, comes from Robinson's Peak, 7 miles southwest of Folsom. An unusual feature are the vesicles filled with nepheline, glass, and pyroxene, (Pl. 3, fig. 1). Megascopically, the rock is a black, dense basalt which shows vitreous nepheline with a hand lens. Microscopically, the texture is holocrystalline, porphyritic, and amygdaloidal. This rock is highest in feldspathoid content of this group (Table 5). Its highly melanic character shows in the high color index accounted for primarily by pyroxene and magnetite. Haüyne occurs in addition to nepheline. The rock is composed of nepheline, haüyne, pyroxene, olivine, magnetite, and, in the vesicles, glass and carbonate. Texturally, euhedral pyroxene, haüyne, and olivine insets lie in a groundmass of small pyroxene crystals, magnetite, and interstitial nepheline. When the slide was stained, all of the low birefringent mineral was blue, thus showing nepheline. It occurs interstitially in the groundmass, and shows square sections in the vesicles. Haüyne forms crystals (.1–.4 mm.),

sometimes colorless but more often brown; centers or rims may be clear but often they are tan-brown with the darkest shade about the outermost rim. High power shows needles or dots of inclusions in rows which protrude either toward the crystal's center or are aligned along cleavage cracks. From the brown alteration color imparted to the crystal, the inclusions may be ilmenite (Rosenbusch, 1905, p. 38). The pyroxene is both diopside and acmite-diopside. It is colorless to pale yellow to pale green, and zoned with the more sodic borders brighter green. Groundmass crystals (.07 mm.), pale yellow-green, are diposide ($Z \wedge c = 37°$). Larger green crystals are acmite-diopside ($Z \wedge c = 63°$). Insets and crystals about the vesicles show zones with colorless cores and bright-green edges; cores being diopside ($Z \wedge c = 40°$), and rims showing their more sodic content by green color and higher extinction angles ($Z \wedge c = 70°$). The residual liquid, has reacted with the earlier formed augite, and thus the rims and later formed pyroxenes in the vesicles carry more of the sodic, acmite-diopside molecule. Olivine occurs in much smaller amount than in the other feldspathoid basalts. Titano-magnetite, however, more abundant than in the other rocks, is scattered throughout the groundmass and forms distinctive granular rims about the vesicles. These vesicles (.5–2 mm.) are irregular or spherical in shape and connected with narrow, tongue-like protuberances. The magnetite borders separate them from the groundmass, and pale-green, long narrow or stubby, sodic pyroxenes, with terminations toward the center, have grown both within and about them. The greater part of the vesicle filling consists of hexagonal, square, or anhedral nepheline which has crystallized in larger, more distinct forms than that of the groundmass. A small amount of yellow-brown glass is associated with these minerals, and carbonate sometimes fills the central part of the amygdules. The mineral aggregates of the vesicles are the same as the groundmass material, but better and larger crystal forms might be accounted for by later and slower cooling, the glass and carbonate in the central portions probably being the last of the constituents to solidify. Passages between vesicles and groundmass show where groundmass material has broken into vesicles and occupied them. Harker (1923, p. 179) pictures an augite andesite from the Isle of Rum, Scotland, in which residual magma has oozed into vesicles and crystallized with a finer texture than the groundmass.

Only small occurrences of nepheline basalt have been reported in the western United States, for instance the knoll in Fairfield Quadrangle and three sills near Stockton, Utah (Gilluly, 1932, p. 48, 62–63), and the knoll at Fort Hall Indian Reservation, Idaho (Mansfield and Larsen, 1915, p. 463). Modes for these rocks are included in Table 5. Cross has given a petrographic description of nepheline basalt associated with nepheline-melilite-basalt and phonolite in Uvalde County, Texas (Vaughan, 1900, p. 3–4).

HAÜYNE BASALT

Haüyne basalt (with equal amounts of haüyne and nepheline) resembles closely in mineralogy the nepheline basalt from Robinson's Peak. Both rocks have high color indices (Table 5), and both carry nepheline and haüyne in slightly different proportions. The haüyne basalt has accessory feldspar.

The haüyne basalt occurs in the saddle between Johnson and Hunter mesas and

on the east side of Hunter Mesa in Hunter Canyon. The specimen examined comes from the saddle and was collected from the low hill at the north end of Hunter Mesa. Olivine basalts are associated with it at the north and south sides of the gap.

Hand specimens are black, fine-grained, slightly vesicular basalt with red insets (1 mm.) of altered olivine. Under the microscope, it is holocrystalline and microporphyritic with insets (50%) of haüyne, pyroxene, and olivine set in a groundmass of pyroxene granules, feldspar microlites and magnetite, with interstitial low birefringent nepheline. This rock carries the highest proportion of haüyne, which together with nepheline makes a total of 13.8% feldspathoid. The percentages of feldspathoid and feldspar are about the same as in the nepheline basalt from Yankee Volcano, from which the rock is separated geographically by Johnson Mesa. A comparison of the modes of these two rocks shows olivine and magnetite present in about the same proportions, and therefore pyroxene accounts for the higher melanic character of the Yankee Volcano nepheline basalt. Mertie (Lee and Mertie, 1922, p. 10) gave the name haüyne basalt to this rock. His Rosiwal analysis (Table 5) follows: augite (61%), magnettie (13%), olivine (10%), labradorite (8%), haüyne (5%), nepheline (3%). He says "the most striking feature of this rock is the scarcity of plagioclase." He also mentions a haüyne basalt on the east side of Hunter Mesa, in Hunter Canyon, and says it is probably a part of the same flow, but that nepheline was not observed, and the percentage of plagioclase was small.

Haüyne crystals (Pl. 3, fig. 2) differ from those in the nepheline basalt only in a more pinkish-tan alteration color of the centers, the rims being usually clear white or colorless. The centers contain minute, metallic inclusions arranged along dodecahedral cleavage planes, and from their similarity to the inclusions in the nepheline basalt, may also be ilmenite. Other inclusions may be small bubbles or gas-filled cavities (Rosenbusch, 1905, p. 38). Insets of pyroxene (.4 mm.) are euhedral, pale-tan clinopyroxenes like those of the olivine basalts, and have grown singly and in clusters. These contain magnetite and groundmass inclusions, more often in centers than around edges. Prominent zones show slightly different extinctions; cores $Z \wedge c = 54°$, pale green middle zones $Z \wedge c = 38°$, outer rims $Z \wedge c = 44°$. Olivine insets (.1 mm.) do not differ from those in the olivine basalts.

OLIVINE-FREE BASALTS

Basalts without olivine, (pyroxene andesites of Lee and Mertie, 1922, p. 10) also were erupted during the Clayton extrusions. These are pale- to dark-gray vesicular rocks which come from the mesa east of Meloche Mesa and Sierra Grande. They contain saturated minerals, and have pyroxene instead of hornblende, with a color index 30+. The modes show they contain only plagioclase, pyroxene and magnetite. Feldspars range from oligoclase ($\alpha = 1.532$) to labradorite ($\beta = 1.560$). A small amount (1.2%) of analcime vesicle filling occurs in the Sierra Grande specimen.

Sierra Grande is the largest cone in the area, and is built of several kinds of lava. The description and determination of the sequence of these flows offers a separate study. The specimen examined in thin section from the Clayton flows of Sierra Grande resembles the olivine basalts from the east end of Johnson Mesa but differs in its lack of olivine; and with so much glass (35%), it is difficult to know whether it belongs with basalts or andesites. The index of refraction of the glass is below

balsam; and according to George (1924, p. 370) andesite glasses have an index below basalt glasses but above balsam. Mertie (Lee and Mertie, 1922, p. 10–11) mentions pyroxene andesite as being a type found on Sierra Grande, but as this mountain lies outside the Raton-Brilliant-Koehler quadrangles, he does not describe the rocks. However, Clarke (1915, p. 150) gives a brief, petrographic description by Cross of a pyroxene andesite from Sierra Grande, Colfax County, which "contains augite, less hypersthene, microliths of plagioclase, apatite, magnetite and a smoky-brown glassy base." The mineralogy of the rock which the writer examined is similar. A chemical analysis of the rock is given by Clarke (1915, p. 150) and Washington (1917, p. 377).

The specimen from the mesa east of Meloche Mesa resembles the holocrystalline olivine basalts, but is nonporphyritic and olivine free. Mertie (Lee and Mertie, 1922, p. 10) described and named the rock on the mesa east of Meloche Mesa augite andesite because it contained andesine feldspar.

In the present classification, these rocks are grouped with basalts because they have pyroxene, and the feldspars and color indices more closely resemble the olivine basalts than they do the andesite described in this paper.

PETROGRAPHIC CORRELATION WITH BASALTS OF THE RATON-BRILLIANT-KOEHLER QUADRANGLES

Petrography corroborates the three main eruptive periods of basalt which Collins establishes from physiographic evidence. Further detailed work may necessitate refinements and subdivisions in this classification. Mertie (Lee and Mertie, 1922, p. 9) designated the three periods of eruption in the Raton-Brilliant-Koehler quadrangles as the first, second and third periods. Collins has grouped together the first and second periods and called them the Raton basalts. Mertie's third eruptive period Collins has called the Clayton basalts. Mertie (Lee and Mertie, 1922, p. 11) recognized a fourth, more recent, eruptive period outside the Raton-Brilliant-Koehler region. Collins designates this last period of eruption as the Capulin basalts.

Mertie's two groups of high-level basalts showed slight petrographic differences and those same variations appear in the Raton basalts to the east. All the rocks are microporphyritic, but the holocrystalline ones with olivine insets only are the most likely to correlate with the earliest (Qb^1) eruptive basalts of the Raton-Brilliant section; the occasionally hyalocrystalline, with insets of pyroxene and olivine and a little occasional biotite, most certainly correlate with the second (Qb^2) eruptive period. Iddingsite, found rarely in the writer's specimens of Raton basalts, was used by Mertie as a partial means to distinguish between his first and second periods. Ross and Shannon (1925, p. 5) believe iddingsite to be a deuteric mineral which has no relation to weathering. It may be abundant in one flow and absent from others above or below, and therefore is not a good mineral with which to correlate, even in part, these basalts when different persons may collect specimens. Mertie's earliest flows differ further from those described in this paper by having a fine-grained (.5 mm.) doleritic fabric. Mertie (personal communication) used the name dolerite for coarse-grained basalt. The basalt which most closely resembles Mertie's description and which certainly corresponds petrographically with his earliest flows,

comes from the high mesa north of Valley Post Office and resembles petrographically the Mesa de Maya basalt with which it was compared. Other Raton basalts, holocrystalline with olivine insets, although finer-grained (.1 mm.), come from Devoy Peak, gap between Johnson and Hunter mesas, mesa east of Dougherty's Ranch at Herefore Park, and the west end of Johnson Mesa. They probably are the same as, or continuations eastward of Mertie's earliest basalts.

Two periods of flow, classed here as Raton basalts, occur on Johnson Mesa, for the west end of the Mesa represents the highest level and is capped by oldest basalts, while the north end lies about 500 feet lower (Lee and Mertie, 1922, p. 4) and has petrographically slightly different basalts. The basalts with augite and olivine insets, and sometimes only partially crystallized, belong to this second, lower-level, eruptive period of Mertie. Petrographically similar basalts come from the south edge of Mesa Llargo, and farther east those found at Oak Canyon and on Devoy Peak could correlate with Mertie's earliest flows. No pronounced chemical or mineralogical difference exists between these two groups; the main variance is textural. The widespread Clayton basalts of intermediate age show the same petrographic features as those Mertie describes in the Raton-Brilliant area. Those from Yankee Volcano, and the gap between Hunter and Johnson mesas show no differences from his rock descriptions. Essentially the same lavas extend southward and occur at Blosser Mesa and Gap, the vicinity of Temples Peak and Joe Cabin Arroyo. They extend eastward to Sierra Grande, are found in the Hereford Park area on Robinson's and Burnt Mountains and Emory Peak. Explosive activity is represented in the volcano at the head of Brigg's Canyon.

A variety of olivine basalts belong to the area east—they were likewise recognized in the Raton-Brilliant section; all correlate as Clayton, low-level, intermediate basalts, third eruption period of Mertie. Quartz inclusions occur in olivine basalts from Yankee Volcano and Emory Peak, and also in nepheline basalt from Yankee Volcano. Nepheline basalt recorded from Yankee Volcano and haüyne basalt from Hunter Mesa and Gap have correlatives to the east in nepheline basalt on Robinsons' Peak, and other feldspathoid lavas are known on Emory Peak, Sierra Grande, and in the Don Carlos Hills. Closely allied as an undersaturated, melanic rock is the analcime basanite from Pittsburgh, south of Chico. Olivine-free basalt from the mesa east of Meloche Mesa is, no doubt, the same rock which Mertie describes as augite andesite (Lee and Mertie, 1922, p. 10), but here it has been included with the basaltic rocks.

The later Capulin basalts belong to this area, and do not occur to the west. Thinner flows and more explosive activity marked this final epoch. Its association with the lowest, present-day degradation levels and its more explosive nature, reflected in textures of the rocks, makes this closing volcanism distinctive in northeastern New Mexico.

RED MOUNTAIN DACITES

GENERAL STATEMENT

Specimens were examined from Towndrow Peak, Red Mountain (sometimes called Bell Mountain), both on Johnson Mesa, the main mass of Cunningham Butte and the dike which strikes northwest from it, Green Mountain, Laughlin Peak, Palo Blanco and its central neck, and Raspberry Peak.

Mertie (Lee and Mertie, 1922, p. 10–11) gave the name dacite to glassy rocks from Towndrow Peak, Cunningham Butte, and Green Mountain because a glassy base composes nearly half the rock, and a chemical analysis of a similar rock from Red Mountain shows 67% SiO_2 which is about the average percentage of silica in dacites. Rocks almost identical with those Mertie described are found as flows on cones and plugs outside the Raton Quadrangle.

MINERAL COMPOSITION

General Statement. The rocks described in this section might be named andesites if classified according to actual minerals developed, or dacites by comparison with the chemical analysis and indicated potential mineral composition of the similar rock from Red Mountain. An incomplete chemical analysis was made of the rock from Cunningham Butte to determine the percentages of silica and alkalies. The analysis and that given by Mertie of the rock from Red Mountain follow:

	Dacite Red Mountain, Colfax County, New Mexico (J. G. Fairchild, analyst)	Dacite Cunningham Butte, Colfax County, New Mexico (H. Stobbe, analyst)
SiO_2	67.98	66.01
Al_2O_3	15.53	14.57
Fe_2O_3	2.68	4.16 } Total iron
FeO	.18	} oxides as Fe_2O_3
MgO	1.47	.20*
CaO	3.39	3.71
Na_2O	4.53	5.24
K_2O	3.00	2.34
H_2O-	.11	u.d.
H_2O+	1.05	u.d.
TiO_2	.34	u.d.
CO_2	—	u.d.
P_2O_5	.33	u.d.
S	—	u.d.
MnO	.04	u.d.
Total	100.63	96.23

* There may have been a loss in magnesium.

From these analyses the calculated mineral percentages are as follows:

	Dacite from Red Mountain	Dacite from Cunningham Butte
Quartz	21.90	20.82
Orthoclase	17.79	13.34
Albite	38.25	44.01
Anorthite	13.07	9.45
Diopside	1.51	
Wollastonite		3.71
Hypersthene	3.00	.50
Hematite	2.68	4.00
Magnetite		
Ilmenite	.46	
Apatite	.67	

C.I.P.W. Symbol I ^{1}4.2.4.Lassenose.

Taking 10% of quartz as the dividing line between andesites and dacites, these lavas are dacites, although neither quartz nor orthoclase appears in the mode.

Hand specimens are pale- to medium-gray, fine-grained, compact, porphyritic rocks with dark hornblende insets (longest 9 mm.) and sparse feldspar (3 mm.)

TABLE 6.—*Modes of dacites*
(Volume Percentages)

Number	Brown hornblende dacites				Green hornblende dacites			Brown hornblende "vitrophyres"		
	1	2	3	4	5	6	7‡	8	9	10
Plagioclase	28.3	28.6	28.7	28.0	49.4	49.5	54.7	15.0	19.1	18.0
Hornblende	9.6	18.2*	9.7	6.8	4.6	4.6	6.3	1.6	1.9	1.4
Magnetite	4.2	3.6	4.4	3.2	3.5	8.5	6.0	1.8	2.5	2.2
Glass	57.9	49.6	57.2	62.0	42.5	37.4	33.0	82.6	76.5	78.4
Color Index†	(14)	(21)	(14)	(10)	(8)	(13)	(12)	(3)	(4)	(4)

1. Towndrow Peak, from lower bench on east side.
2. Top of Towndrow Peak.
3. Red Mountain.
4. Southwest side of Palo Blanco.
5. Green Mountain, northeast slope.
6. Dike extension of Cunningham Butte.
7. Main mass of Cunningham Butte.‡
8. Laughlin Peak.
9. Northeast side of Laughlin Peak.
10. Top of Laughlin Peak.

* 7.5% hornblende altered to magnetite.
† See footnote 1.
‡ Analyzed specimen.

insets. Microscopically, they are hypocrystalline and porphyritic, with insets of hornblende and plagioclase in a groundmass of feldspar, hornblende, scattered magnetite, and colorless to tan glass.

Three varieties occur. One group (Table 6, nos. 1–4) has brown hornblende, andesine to labradorite, and about 50% of glass (Pl. 3, figs. 3, 4). The second group (Table 6, nos. 5–7) has green hornblende, oligoclase, and about 37% of glass. Other similar flows may be varietal or transition types. The third group (Table 6, nos. 8–10), from Laughlin Peak, is vitrophyric (78% glass) and more leucocratic with less hornblende. Dacites with brown hornblende are most abundant and occur as flows on cones; those with green hornblende are found as volcanic plugs or necks. Brown, ferric hornblende can be produced by heating green hornblende to 750°, resulting in oxidation of iron and loss of water (Kozu, Yoshiki, and Kani, 1927, p. 143). As the brown hornblende occurs in flows, it may have been oxidized by higher temperatures. Average modes (volume percentages) follow:

	Brown hornblende dacite	Green hornblende dacite
Plagioclase	28.4	51.2
Hornblende	11.1	5.2
Magnetite	3.8	6.0
Glass	56.7	37.4
Color Index	(15)	(11)

Brown hornblende dacites have built up such cones as Red Mountain, Palo Blanco, Towndrow and Raspberry Peaks. Modes and degree of crystallinity of four typi-

cal specimens (Table 6) are quite consistent. Green hornblende dacites occur as the plug and dike extension of Cunningham Butte and neck in the center of Palo Blanco. The modes of these rocks (Table 6) show less hornblende, more plagioclase, and less glass. Lavas from Green Mountain and the southwest spur of Palo Blanco have brown and green hornblende. The mode (Table 6, no. 5) of Green Mountain lava resembles that from a dike extension of Cunningham Butte (Table 6, no. 6). The lavas from Green Mountain and southwest spur of Palo Blanco differ slightly from either group. They could be transition or varietal types because Palo Blanco is built essentially of brown hornblende dacite with a central neck of green hornblende dacite, and Green Mountain has close field proximity to Cunningham Butte, not far to the southeast. Mertie (Lee and Mertie, 1922, p. 10) describes a similar rock from Green Mountain flows as a "siliceous igneous rock." He says a chemical analysis is needed to determine the petrographic family, but the rock closely resembles the dacites and probably belongs to this group.

More leucocratic (color index 3), highly glassy flows with oligoclase, andesine, and hornblende occur on Laughlin Peak, southeast of Green Mountain. Hand specimens are pale-gray and pink-banded, fine-grained, vesicular rocks. Microscopically, minerals and fabric resemble the dacites, but because of the large proportion of glass and lack of chemical data they are called vitrophyres. A chemical analysis of the Laughlin Peak rock might show a high silica content which would warrant the name soda-rhyolite or rhyo-dacite.

Feldspar.—Three generations of feldspar occur; early insets (2 mm); groundmass crystals (.6 mm); and latest microlites. The latter are oligoclase, as indicated by extinction angles (5°) measured from their direction of elongation (a-axis). They show ragged, irregular ends, and parallel flow alignment. Groundmass crystals are andesine (An_{32-42}; extinction $\perp 010 = 15°–20°$). Crystals are beautifully zoned and in the dacites with brown hornblende, cores of insets are labradorite (An_{60}) and rims andesine (An_{38}). The calcic cores gave extinction angles ($\perp 010 = 30°$, and $(+)\ 2V = 76°$; and the andesine rims, angles ($\perp 010 = 16°$) and $(+)\ 2V = 87°$.

Andesine ($\alpha = 1.553$; $\gamma = 1.560$) occurs in all of these rocks. No feldspar as calcic as labradorite occurs in the green hornblende andesites, which agrees with their slightly more felsic character.

Carlsbad and albite twins are common. Complex twinning is sometimes shown, for albite lamellae superposed on individual Carlsbad twins may wedge out abruptly, so that in groups the effect is that of pericline twinning. Some crystals, particularly in the green hornblende andesites, show no albite lamellae but have a wavy extinction.

Hornblende.—The strongly pleochroic yellow-red-brown variety, and the green hornblende occur.

Red hornblende, distinguishing one group of these dacites, occurs in the groundmass and as insets, which are long, narrow, euhedral crystals (2 mm.) or transverse sections. It is strongly pleochroic, x = yellow, y = brown, z = red-brown with $x < y < z$. $Z \wedge c$ is small 0°–1°. Two sections gave 9°. One section measured on the U-stage $(-)\ 2V = 84°$. This mineral might be called basaltic hornblende or oxyhornblende (for which Rogers, 1940, p. 826–828) suggested the new mineral name, lamprobolite). Most of these crystals have grown singly, but some as clusters.

Only a few small altered hornblendes occur in the Laughlin Peak flows; the kernels show the brown variety. Hornblende in these rocks is generally fresh, but some late-stage magmatic alteration has produced magnetite rims, and completely replaced some smaller grains. The andesite from the top of Towndrow Peak shows the greatest alteration of this kind, and the mode shows 18% of hornblende, 7.5% of which is now represented by magnetite. Smaller crystals become replaced completely, and only kernels of the largest crystals remain (Pl. 3, fig. 4).

The other hornblende is bright, grass-green, and appears in basal sections or euhedral, long, narrow crystals, sometimes magnetite-rimmed. It is pleochroic with $x = y$ = greenish-tan, z = green with $x = y < z$. Extinction angles ($Z \wedge c$) average 18°, with a range from 15° to 21°, and the optic angle measured on one crystal on the universal stage gave $(-)\ 2V = 45°$. Zones of darker-green centers and lighter edges show in some crystals. Magnetite grains form inclusions and rims about the hornblende. It is also scattered finely but abundantly throughout the rock, in larger proportion (6%) than in the red-hornblende andesites (4%).

A few specimens, such as those from Green Mountain, have two kinds of hornblende, a brown variety with pleochroism x = yellow, y = brown, z = red-brown, and small extinction angle ($Z \wedge c = 4°$); and a brown-green with pleochroism x = green-yellow, y = green and z = red-brown with larger extinction angle $Z \wedge c = 21°$. The brown hornblende is not as brilliant in color or pleochroism, nor are the crystals as large as in the Towndrow Peak variety. Its extinction angle corresponds better with basaltic hornblende than with common hornblende, and the mineral may be partially oxidized hornblende or oxyhornblende (Winchell, 1933, p. 252–254). The brown-green variety has properties of common hornblende and in some slides is the more prevalent.

Magnetite.—The modes show that magnetite occurs quite constantly (5%). It is scattered as granules and squares, as inclusions in hornblendes, forms borders about these, and in some cases has completely replaced all but the cores of larger hornblende crystals.

Glass.—Glass forms an important constituent of these rocks; and its potential mineral composition should aid in determining the rock name. It forms a colorless to tan, isotropic base with incipient feldspar microlites. Crushed fragments from the brown-hornblende dacites give a refractive index between 1.510 and 1.496; those from the green-hornblende dacites give indices between 1.518 and 1.522.

Following George's chart (1924, p. 365), a glass with an index 1.510 and 1.496 might hold from 69% to 73% silica; and one with an index of 1.522, 64% silica. This leaves little doubt of the high silica content of the glass.

The average index of dacite glass according to George is 1.511, with a range from 1.504–1.529; that of andesites 1.512—with range from 1.489–1.529. In general the index is lower, the higher the silica content. In the New Mexican rocks the index range of the glass in brown hornblende dacites is 1.496–1.510 and that in green hornblende dacites is 1.518–1.522.

TEXTURE

These rocks are all hyalocrystalline, porphyritic rocks. Both hornblende and plagioclase form insets (2 mm). Flow structure is prominent in most of the speci-

mens, especially in those with brown hornblende, and shows particularly well about large crystals. The most glassy rocks, those from Laughlin Peak, have flow layering and tannish-brown glass streaks which show incipient crystallization.

Feldspars have square or rectangular forms. Many of the larger crystals show transverse, glass-filled cracks, which indicate earlier age than groundmass crystals and microlites. Sudden chilling as the lava erupted at the surface may have caused cracks which subsequently were filled with glassy residuum. Groundmass material also forms inclusions in cores or borders of feldspar insets (Pl. 3, fig. 5).

Insets, not numerous but prominent, make irregular boundaries with the groundmass. In plane light they appear to be single crystals; under crossed nicols, glomeroporphyritic texture is apparent with several, differently oriented crystals grouped together. Coombs (1936, p. 178), in describing similar crystals from Mt. Ranier andesites, suggests that "the phenocrysts were formed by the accretion and welding together of smaller feldspars of an earlier generation." This may hold for some feldspar groups in the andesites, but other crystals show definitely their individuality. Their more calcic composition indicates that they formed before the smaller crystals, and that the rims grew more sodic through continuous magmatic reaction. These crystallized first from the magma, then those of intermediate size, and, last, the microlites.

HORNBLENDE ANDESITE

A hornblende andesite (Pl. 3, fig. 6) was collected from the top of the southwest flank of Turkey Mountain, 8 miles northwest of Chico in eastern Colfax County. Megascopically it is gray-green and porphyritic with dark, ferro-magnesian insets (10 by 5 mm). Microscopically, it is holocrystalline with a fine-grained cryptocrystalline groundmass with insets (50%) of hornblende, pyroxene and rarer feldspar. Less than 1% of red-brown biotite is associated with both pyroxene and hornblende. The feldspar is basic andesine to labradorite with an index of refraction less than 1.564 and greater than 1.570. Pyroxene occurs in small groundmass granules and insets of an earlier generation. Insets are colorless to pale green, and nonpleochroic with extinction ($Z \wedge c = 47°$. They show alteration or corrosion effects, with the usual freeing of iron oxide. Long narrow euhedral hornblende crystals show pleochroism x = light brown, y = greenish-brown, z = greenish-brown with absorption $x < y < z$. Extinction angles ($Z \wedge c$) average 25°, but vary from 19° to 25°, and are not constant within crystals. Edges give higher extinction angles ($Z \wedge c = 29°$) than cores ($Z \wedge c = 23°$). Magnetite is scattered throughout the rock, associated with pyroxene insets and as rims about hornblende crystals. Euhedral apatite crystals are prominent. Pyroxene, labradorite feldspar, and color index (29) show that this rock approaches basalt in composition. It is called an andesite because of its hornblende content.

SLAGLE TRACHYTES

GENERAL STATEMENT

Specimens were examined from Slagle Canyon, Red Hill, Joe Cabin Arroyo, and Turkey Mountain, and were found to be soda trachytes.

MINERAL COMPOSITION

General Description.—The name soda trachyte is here used for fine-grained, leucocratic rocks composed of soda orthoclase, oligoclase-andesine, amphibole, and/or pyroxene. Hand-specimens are pale-gray to light-tan, fine-grained or compact rocks, with porphyritic texture, insets of chalky white feldspars (1–9 mm long) and dark, needle-like hornblendes of about the same size. Microscopically, they are fully crystallized and porphyritic, with insets (4%) subordinate to groundmass. A Rosiwal analysis of the soda trachyte from Red Hill shows feldspar (87.5%), pyroxene (2.9%), hornblende (1.5%), magnetite (7.7%), apatite and sphene (.4%), with a color index of 12. A little quartz occurs in irregular patches or filling cavities.

Insets are oligoclase-andesine, acmite-diopside and brown hornblende. Pyroxene and hornblende carry euhedral apatite and magnetite inclusions. Groundmass feldspars in some of the specimens have trachytic structure, in others they are arranged radially in sheaves which give a rosette or feathery pattern to the rock.

Lonsdale (1940, p. 1579–1587) has described soda trachytes from the Terlingua-Solitario region, in the southern part of the Big Bend country of Texas. His modes show soda orthoclase (72%–89%), which compares with 88% (total feldspar) in the New Mexican soda trachytes, also aegirine-augite, riebeckite, arfvedsonite, and quartz. Although the Texas rocks differ slightly in mineralogy from those of New Mexico, they are of interest as soda trachytes which occur in the same alkaline belt (Fig. 3) as the sodic rocks described in this paper.

Feldspar.—Groundmass feldspars are turbid in plane light because of incipient alteration or zeolitization; under crossed nicols they show wavy, patchy extinction characteristic of soda-rich feldspars (soda orthoclase). Rare patches show albite lamellae. A little groundmass feldspar is oligoclase ($\gamma = 1.550$) extinction ($\perp$ 010) = 5°. Under high power, stringers and blebs of soda feldspar can be seen penetrating the host laths, forming cryptoperthitic textures and rims around some larger laths.

Insets, patchy and partially replaced by albite, are oligoclase-andesine, with finely striated cores of andesine (An_4); extinction ($\perp$010) = 23°. Outer portions are more sodic, as shown by the oligoclase-andesine composition (An_{32}) indicated by extinction angles ($\perp$010) = 16°. Rims of wavy, perthitic anorthoclase or soda orthoclase border these crystals and make irregular, serrate edges with groundmass feldspars, merging inconspicuously into the groundmass. They have not grown in optical continuity with the oligoclase-andesine crystals, and appear as portions added to the crystals during solidification of the residual, soda-rich, magmatic material.

Albitization of the oligoclase-andesine insets has produced a checkerboard or patchy appearance; small albite patches (less than 1%) occur irregularly in the groundmass. The index of refraction is always lower than those of Canada balsam and the twinned oligoclase-andesine. This lower index ($\alpha = 1.528$; $\gamma = 1.540$) gives higher relief to the albite than in other feldspars. Where solutions have penetrated along cleavage cracks, the patch-work or checkerboard perthites appear, similar to those pictured and described by Andersen (1928, p. 151) from the granite pegmatites of Norway. Under high power, one can see islands of twinned andesine, embayed and surrounded by untwinned albite. Albitization, to less extent, has also taken place in the groundmass; stringers thread from insets into groundmass feldspars and small, clear, iner-

stitial patches of albite have a higher index than enclosing anorthoclase. Only occasionally can twin lamellae be detected with high power; if this kind of twinning is present, it is submicroscopic.

Pyroxene.—Pyroxene and hornblende occur in the same rock. Pyroxene is more abundant in the flow from Red Hill and subsidiary to hornblende in the trachyte intrusive in Slagle Canyon.

Pyroxene occurs in the groundmass sparsely, and as euhedral, single, or clustered insets. Optical properties show colorless or pale-green, unevenly colored, nonpleochroic acmite-diopside. Often the cores are colorless diopside, with extinction angle ($Z \wedge c$) = 38° and (+) 2V = 58° measured on the universal stage. Pale-green rims have a more sodic composition, as shown by the lower extinction angle ($Z \wedge c$) = 32°–35° and the larger optic angle (2V = 70°). These properties show that the rims hold more of the acmite molecule than the cores. Sometimes the entire crystal is green acmite-diopside. These crystals usually carry magnetite, apatite, and groundmass inclusions.

Hornblende.—Hornblende is more abundant than pyroxene in some rocks, for instance the trachyte sill from Slagle Canyon. Optical properties suggest it may be barkevikitic, for it is pleochroic with x = pale brown, y = greenish brown, and z = olive-green, and extinction angle ($Z \wedge c$) variable from 10°–18°; one reading gave 23°. This variability is often met in hornblendes with high alkali content. Groundmass hornblende is usually in small, altered patches. Large crystals are long, narrow, and euhedral; they show prominent zoning with dark-brown interiors, surrounded by magnetite rims, bordered by lighter-tan hornblende with outermost edges of magnetite granules. Corrosion has completely removed the centers of some crystals; in others, included euhedral magnetite and apatite crystals suggest that hornblendes grew around these minerals.

Accessories.—Magnetite is fairly abundant (8%). It occurs as euhedral grains in both pyroxene and hornblende, and scattered throughout the rock. Apatite and sphene are present in small amounts.

CHICO PHONOLITES

GENERAL STATEMENT

Specimens were examined from Temples Peak, Pecks Mesa, 4 miles south of Temples Peak, Strongs Canyon, Joe Cabin Arroyo, Slagle Canyon, Red Hill east of Slagle Canyon, and the south flank of Laughlin Peak. A tinguaitic variety comes from Kiowa Mesa and an ocellar analcime phonolite from Timber Buttes, about 2 miles southeast of Laughlin Peak. The specimen from Timber Buttes was collected 2 miles southeast of the Buttes, one-half mile east of the Chico-Mesa Llargo Road, on the headwaters of Palo Blanco Creek. The mode (Table 7, No. 8) does not differ greatly from that of the other phonolites, allowing for nepheline and analcime being measured together as feldspathoid content.

MINERAL COMPOSITION

General Description.—Phonolite is here used for leucocratic rocks (color index 15) composed of alkali feldspars, feldspathoids, and sodic pyroxenes. Hand specimens

differ in appearance. Some are greenish-gray or green, fine-grained or dense with a vitreous luster. Commoner are porphyritic green rocks with feldspar insets (4 mm–1 cm.), which are clear with pearly luster when fresh, but when weathered are chalk-white with pronounced zoning, and protrude above the surface. Often these feldspars are bunched irregularly, or aligned with their flat faces parallel to the flow direction.

TABLE 7.—*Modes of phonolites*
(Volume Percentages)

Mineral	1	2	3	4	5	6	7	8
Feldspathoid (nepheline chiefly)	49.6	45.5	17.0	50.6	32.9	52.6	19.6	48.6
Feldspar	28.6	44.1	71.3	35.0	47.2	40.4	64.6	32.9
Pyroxene	21.8	10.4	11.7	14.4	15.6	7.0	15.8	17.7
Magnetite					4.3			.2
Sphene								.6
Color Index*	(22)	(10)	(12)	(14)	(20)	(7)	(16)	(18)

1. South base of Laughlin Peak.
2. Top of Temples Peak.
3. Top of South Point of Temples Peak.
4. West side of Strong's Canyon.
5. Northeast of Chico.
6. Temples Peak flows.
7. Red Hill.
8. Timber Buttes.

* See footnote 1.

Microscopic examination and modes (Table 7) of the phonolites show feldspathoids, feldspars, pyroxene, magnetite, and sphene. Nepheline is the most abundant feldspathoid but analcime also occurs; feldspars are soda orthoclase; pyroxenes are aegirine and more rarely acmite-diopside. A common variety of phonolite has a groundmass of feldspar laths and interstitial nepheline in which are set larger aegirine crystals. Average modes show feldspathoids and feldspars in nearly equal proportions. Individual modes (Table 7) indicate how these minerals vary; nepheline ranges from 17%–52% and feldspar from 28%–71%, being correspondingly lower the higher the nepheline content. In measuring stained slides, feldspathoids include nepheline and analcime, and minor alteration minerals from nepheline. Accessories are those commonly found in phonolites. A mineral of the sodalite group is scattered abundantly in the slides as small, dusty, isotropic hexagonal sections, and may be nosean, sodalite, or haüyne. Cancrinite, colorless to pale yellow is in shreds and pieces, usually associated with nepheline. Zeolitic products make streaked alteration effects on both nepheline and soda feldspars. Sphene is not abundant; small amounts in wedge-shaped crystals and irregular patches occur in the ocellar phonolite from Timber Buttes. Magnetite is sparse or wanting. A yellow to red, vividly pleochroic mineral occurs in small, sharp-edged pieces, sometimes with magnetite or aegirine. It was not identified, but may be one of the rare, orange minerals sometimes found in sodic rocks. Analcime occurs as stringers and cavity fillings, and as ocelli in the rock from Timber Buttes. A little carbonate is also present.

Feldspar.—Laths and insets are tan or turbid in plane light, and laths under crossed nicols show Carlsbad twinning. All crystals show wavy extinction, and may exhibit crepe, perthitic effects. It may be that these feldspars are soda orthoclase with

variable proportions of albite, as Daly (1925, p. 49) found in the soda trachytes of Ascension Island, and similar feldspars in the phonolites of St. Helena Island (Daly, 1927, p. 31–92). The largest insets, in the porphyry from Chico Breaks, show faint, polysynthetic twinning which gives the "gridiron" or "quadrille" structure characteristic of sodic orthoclase. This twinning was detected rarely in the insets in the phonolites which occur as flows.

Zeolitization and analcitization have altered feldspar insets, as in the phonolites from Temples Peak, the base of Laughlin Peak and Kiowa Mesa. Long, narrow single crystals are microperthitic, with feathery zeolites penetrating the whole crystal, or limited to a border. Clear interiors show irregular patches of blotchy anorthoclase and analcime stringers. Clusters of feldspars show a mosaic or checkerboard effect, either entirely or in zonal relations. When zoned, the sodic cores are turbid and the rims clear in plane light; under crossed nicols, these borders appear as a low gray polarizing aggregate of zeolitic material, and the cores are feldspar being replaced by low gray or isotropic analcime. A little carbonate is sometimes associated with this alteration.

Nepheline.—Good euhedral crystals, in square and six-sided sections, and anhedral patches of nepheline occur. The lowest feldspathoid percentages came respectively from the phonolite from the south point, at the top of Temples Peak, and from Red Hill. Other phonolites showed from 33% to 52% (Table 7), with an average about 40%, so that feldspathoid about equals feldspar. Staining brought out zones in some nephelines, as in the specimen from Strong's Canyon. Certain bands were lighter, others darker blue, but all followed the crystal outline. Shand (1939, p. 512) has found that zoned nepheline in phonolites "is due to the rhythmic deposition of layers of nepheline-substance alternately richer and poorer in silica."

Analcime.—Analcime is a part of the feldspathoid content in the modes in Table 7. It has greater relief than nepheline, because of its lower index, and is isotropic or shows slight anomalous birefringence in ocelli. It commonly fills interstices and veinlets, particularly in the flows northeast of Chico, at Strong's Canyon, and the south foot of Laughlin Peak. Analcime ocelli (Pl. 4, fig. 1) occur in the Timber Buttes rock, are round or oval, single or in groups, with connecting analcime stringers, and are always bordered with aegirine crystals. Analcime is water-clear, shows rectangular cleavage, uniform isotropism in smaller crystals, but anomalous birefringence in larger ocelli gives an aggregate appearance. Turbid, zeolitic alteration affects some of the analcime. A specimen of analcime foyaite with similar ocelli, (analcime nepheline syenite porphyry of Timm, 1941, p. 37–40), in the Columbia University collection, comes from the Cornudas Mountains, a small group of eroded laccoliths on the Texas-New Mexico border. Lonsdale (1940, p. 1600) describes and pictures biotite-bordered analcime ocelli, in a syenogabbro. He believes the analcime is magmatic in age, because it associates with biotite, aegiritic pyroxene, and alkali feldspar.

Pyroxene.—Aegirine, the usual pyroxene, is the typical dark mineral of the phonolite flows, but the large crystals in the Timber Buttes phonolite are acmite-diopside (Pl. 4, fig. 1). Aegirine averages 15% and modes show it to vary from 7% to 21%, being most abundant in the phonolite from the base of Laughlin Peak. In general

it is fairly uniform in proportion and often distributed in flow bands (Pl. 4, fig. 2). It is beautifully pleochroic, x = dark green, y = light green, z = yellow-green with $x > y > z$; $X \wedge c = 0°–4°$, average = 2°. Some crystals (.5 mm) have grown singly, others, especially at Laughlin Peak, in radiating clusters (Pl. 4, figs. 3, 4). Most crystals are euhedral, with prism faces and good terminations, although occasionally the ends are ragged. Euhedral inclusions of nepheline (Pl. 4, figs. 3, 4) are common, indicating late crystallization of aegirine. In some phonolites, aegirine is in thin green needles (.4 mm) scattered abundantly through the rock or matted into clumps as in the Timber Buttes phonolite and the tinguaitic variety from Kiowa Mesa (Pl. 4, fig. 5).

Acmite-diopside ($X \wedge c = 38°$) occurs in phonolites from Timber Buttes. Crystals are typically variegated, bordered, and zoned. Cores are often colorless ($X \wedge c = 29°$), indicating diopsidic composition, while the crystal grades to lighter green, and finally bright, grass-green borders ($X \wedge c = 10°$) showing increase in the soda content. Green portions show pleochroism, x = bright, grass green, y = light green, z = yellowish green. Some large crystals are wholly green ($X \wedge c = 35°$). Inclusions of magnetite and nepheline occur.

Magnetite and Sphene.—Magnetite and sphene are scarce and virtually absent from rocks such as that at the base of Laughlin Peak. Occasional irregular magnetite patches occur in the flows associated with Temples Peak, Red Hill and the Chico region. An unidentified orange mineral also occurs in these lavas.

TEXTURE

Textures in the phonolites are the most varied and interesting in the area. Specimens collected over 8–10 miles of the same flow on the west side of Temples Peak show such differences that one wonders if they belong to the same mass. These different megascopic features become more pronounced under the microscope. All the rocks are holocrystalline, with groundmass usually predominant over insets. Insets are soda orthoclase or anorthoclase, and aegirine or more rarely acmite-diopside. Some rocks consist of a mat of streamlined feldspar laths, euhedral and interstitial nepheline, aegirine crystals, and feldspar insets; others have a groundmass of feldspar sheaves; still others have radiating crystals of aegirine.

Porphyritic textures are the most common, and are best exemplified in the phonolites about Temples Peak, Chico Region, Red Hill east of Slagle Canyon, and Peck's Mesa. Feldspar insets are common but smaller crystals also occur.

Flowage is pronounced under the microscope; both feldspar and pyroxenes show alignment. Feldspar microlites and laths, individually bent and twisted, give beautiful trachytic texture. Aegirines in all sizes, usually single but some in groups, are scattered in different directions through the rocks. Many show flow alignment, as in the lavas from Red Hill (not to be confused with Red Mt.) and Peck's Mesa.

Individual minerals show great variety in growth habits. Nepheline occurs in all the rocks, either interstitial, in squares, or six-sided crystals in the groundmass. Aegirine has developed differently in various rocks, no doubt because of conditions before or during extrusion. These varied habits belong to rocks which differ megascopically. For instance, rocks with aegirine bunches are usually the dense, vitreous,

nonporphyritic green rocks such as that from the south side of Laughlin Peak, or the light-gray, mottled "pseudo-schistose" rocks, such as those 1 mile northeast of Chico. More uniformly distributed aegirine belongs to the gray-green, porphyritic flows, as those from Red Hill and Peck's Mesa.

Various sized feldspar crystals are found, depending probably somewhat on the thickness of flows. At least two generations of feldspar occur; there are the intratelluric insets (1 cm.), which are the oldest, smaller, but also probably old insets, and last, the sheaves of groundmass laths and the smallest crystals which make flowage so prominent.

Texturally different from any of the other rocks is the ocellar analcime phonolite with acmite-diopside crystals from Timber Buttes. Ocelli, round or oval, single or in groups, often connected with analcime stringers, are bordered tangentially with aegirine crystals. They are believed to have been bubbles or gas vesicles in the crystallizing magma, later filled with the products of the last residual liquid. Lonsdale (1940, p. 1598, 1600) has described analcime ocelli in the intrusive rocks of the Terlingua-Solitario region, Texas.

TINGUAITE

Tinguaites show no sharp distinction from phonolites, texturally, chemically, or mineralogically. Femic constitutents range for phonolites from 3.5%–26%; for tinguaites from 3.9%–37% (Washington, 1917). Rosenbusch (1887, p. 627–628; 1907, p. 607–608, 615) gave the name tinguaite to rocks from Serra de Tinguá, Brazil, and differentiated them from phonolites because of more fine aegirine needles scattered through the rock. The rock described in this section is described separately because it occurs as a sill with the resulting textural difference.

The sill is exposed on the east and west sides of Slagle Canyon, 3 miles north of the bridge, and is related to the history of the peralkaline rocks. It is a very fine-grained, compact, green rock. Microscopically it is holocrystalline, composed of an aggregate of euhedral nepheline, feldspar, and abundant aegirine needles which outline, lie between, or penetrate the other minerals. The abundance of aegirine gives the thin section a moss-like appearance, and a green color to the hand specimens. A slide was made and stained to show the nepheline clearly.

Finlay (1904, p. 280–282, 302–304) describes and pictures similar tinguaites among the alkaline rocks at San José, Tamulipas, Mexico.

ANALCIME MICROFOYAITES

GENERAL STATEMENT

Analcime microfoyaites are grouped separately from the phonolites because of their intrusive origin and petrographic differences. They are a little coarser than the phonolites, and rosette and hypidiomorphic mineral patterns occur. Analcime is found in triangular, intersertal patches. Nepheline is present but difficult to detect because of analcitization. After staining, nepheline could sometimes be detected from analcime because of its birefringence.

The rock closest petrographically to the phonolites forms a sill in Slagle Canyon;

it differs only in having analcime, and a rosette and intersertal rather than trachytic texture. A sill in Joe Cabin Arroyo carries nepheline and has a fine-grained, hypidiomorphic texture. The most divergent rock, mineralogically, comes from a small, isolated knob in the Chico region. It is porphyritic with groundmass of orthoclase, soda orthoclase, acmite-diopside, interstitial analcime, and carbonate, granular magnetite; insets of oligoclase-andesine, brown hornblende, and rarer acmite-diopside. The name analcime microfoyaite is used for these fine- to medium-grained intrusives composed of analcime, nepheline, alkali feldspars, soda pyroxenes, and/or amphiboles.

Analcime (index = 1.488±) is colorless, clear, and isotropic. It is not sodalite for an uncovered slide, treated with a solution of nitric acid and silver nitrate, gave no white, silver chloride precipitate. Analcime was confirmed further, and its extent detected by treating with phosphoric acid and methylene blue.

The occurrence of these rocks in small bodies suggests their intrusion below a relatively thin sedimentary cover. The magma from which they solidfied was evidently a soda-rich solution, high in water content, toward the final stages of consolidation; analcime filled wedge-shaped places, between already crystallized minerals, and also partially replaced feldspars. Lonsdale (1940, p. 1598) describes similar triangular patches of analcime, and says "In the later stages of crystallization, the magmas possessed an analcite-rich residual fraction in the interstices between earlier formed crystals." At this stage, final consolidation of many of the smaller masses occurred without much reaction between liquid and crystals, and with an effect much like that of a laboratory 'quenching experiment.' Quick cooling, or "quenching," which prevents the escape of water, may explain the triangular, interstitial analcime in these microfoyaites.

The analcime is believed primary because of its intersertal habit. Scott (1916, p. 37, 42), Tyrrell (1912, p. 71; 1917, p. 127; 1923, p. 249), and Walker (1923, p. 243, 246) have shown conclusively the primary origin of analcime in the basic rocks and teschenites of Scotland.

MINERAL COMPOSITION

Analcime microfoyaites will be described individually because of their petrographic differences.

A sill in Slagle Canyon is a pale-gray, fine-grained rock with occasional, chalky-white insets (4 by 8 mm) and barely perceptible ferromagnesian needles (1 mm). Specimens came from the main portion of the sill in the east wall, one-half mile north of Chico Road, and from outcrops just north of the Maxwell-Chico Road, one-half mile north of the bridge. Microscopically the rock is holocrystalline, composed of feldspar rosettes, intersertal analcime, aegirine, nepheline, a sodalite mineral, and a little magnetite. Groundmass feldspars and rare insets are turbid in plane light; under crossed nicols they show Carlsbad twinning, wavy, patchy extinction, and cryptoperthitic structures characteristic of soda orthoclase. Some interstitial nepheline is partially or completely analcitized. Analcime, with or without carbonate, fills triangular spaces between other minerals; although isotropic, it sometimes shows slight anomalous birefringence. Grass-green aegirine, in small pieces, shreds, and broken crystals, shows pleochroism x = green, y = yellow-green, z = yellow and

extinction (X ∧ c) = 6°. A mineral of the sodalite group forms six-sided, dusty, isotropic crystals, scattered throughout the rock and included in aegirine. This rock is similar to, but finer-grained than, an analcime nepheline foyaite (analcite-nepheline syenite of Zapp, 1941, p. 43–46) examined from the Cornudas Mountains.

A sill at the west end of Joe Cabin Arroyo is a fine-to medium-grained, mottled green and pink rock. Microscopically it is holocrystalline with hypidiomorphic texture. Minerals are feldspathoids (5%), feldspar (74.9%), pyroxene (15.8%), and magnetite (5.3%). Clear, Carlsbad-twinned orthoclase occurs and also perthitic soda orthoclase. Some laths have cores of soda orthoclase with perthitic rims. A little albite-twinned plagioclase also is present. Nepheline forms prisms, shows transverse cracks and incipient zeolitization. These features distinguish it from feldspar; its presence was confirmed by staining. Euhedral, green acmite-diopside, is commonly altered to reddish iron oxides. A little analcime forms sharp, triangular patches between other minerals, and sometimes borders nepheline.

Analcime microfoyaite with brown hornblende forms an isolated knob, 2½ miles north of Chico. Megascopically it is green-gray, weathering dull, light brown, and has a fine-grained, porphyritic texture with vitreous feldspar insets (2 by 4 mm) and conspicuous black hornblende needles (1–10 mm long). Microscopically this rock is holocrystalline, porphyritic, with intersertal habit. Minerals are feldspar (37.5%), feldspathoids (39.4%), pyroxene (5%), hornblende (12.1%), magnetite (5.3%), zircon (.5%), and apatite (.2%). The percentage of leucocratic minerals in the mode is therefore 76.9 and that of the melanic minerals 23.1. Carbonate, not measured separately, occurs in triangular patches, associated with analcime and feldspars. Nepheline is difficult to detect. Partially or fully analcitized prisms with transverse cracks resemble nepheline. Groundmass feldspars are orthoclase or soda orthoclase, and have a sheaf-like arrangement. A little albite-twinned feldspar also occurs.

Oligoclase-andesine insets (2 mm long) show both Carlsbad and albite twinning with extinction angles (⊥ 010) = 21°. Analcime in clear, isotropic squares, blocks, and stringers has replaced feldspars. Associated with it are carbonate stringers. Euhedral hornblende insets have pleochroism x = tan, y = red-brown, z = darker brown; x < y < z; Z ∧ c = 15°, suggesting a barkevikitic amphibole. A yellowish red mineral in minute aggregates is associated with some of the hornblende and magnetite, and may be an iron-rich alteration product. Acmite-diopside is essentially the same as that described in the soda trachytes. It is colorless or pale green with x = green, y = pale green, z = light green, and Z∧c = 38°. Some crystals are more intensely colored than others and some have colorless rims (extinction Z∧c = 30°) and green cores (Z∧c = 42°). This mineral occurs in the groundmass and as insets, but smaller than both hornblende and feldspar. Apatite is in euhedral, dusty crystals. Analcime and carbonate both form triangular, intersertal patches and are associated with feldspars.

Alkalies determined in this rock are

$$Na_2O = 8.99\%$$
$$K_2O = 3.73\%$$

All of the potash was used in the calculation of orthoclase, which was found to be 22.06% of the feldspar content (Table 8). In the soda calculations the feldspathoid

percentage (39.4) in the mode, as measured from a stained slide, was considered as analcime. The percentage of Na_2O used in its formation was calculated to be 5.54. The remaining 3.45% Na_2O would yield 29.15% albite. This amount of albite added to the orthoclase gives 13.71% more feldspar than the mode. If, however, the amount of soda (.67) which might be contained in 5% acmite is considered, and a possible 1%

TABLE 8.—*Alkali and feldspar percentages in analcime microfoyaite from isolated knob, 2½ miles north of Chico*

Mineral	K_2O%	Na_2O%	Calculated percentage albite and orthoclase	Calculated total percentage feldspar	Mode
Analcime		5.54			39.4
Acmite		.67			5.0 (acmite-diopside)
Hornblende		1.00			12.1
Albite		1.78	15.04	37.10	
Orthoclase	3.73		22.06		37.5
Magnetite					6.0

allowed for 12% modal hornblende, the 1.78% Na_2O which remains forms by calculation about 15.04% albite. This percentage of albite together with the orthoclase, checks more closely with the undifferentiated feldspar percentage in the mode.

DIKE ROCKS

GENERAL STATEMENT

(A) Basaltic feeders, (B) Leucocratic dikes and (C) Melanocratic dikes occur in the region.

There were no specimens from basaltic feeders because outcrops of these are talus covered. The leucocratic dikes (hornblende dacite, phonolite, tinguaite, and analcime microfoyaites) at Slagle Canyon and Peck's Mesa resemble the alkaline flows and shallow intrusives of the area, and also the Red Mountain dacite cones. Melanocratic dikes include basalt and a number of lamprophyres (vogesites and monchiquite). Mineral composition and texture of this group contrasts sharply with the leucocratic dikes. Specimens were examined from south of Blosser Gap in Colfax County, the west side of Slagle Canyon, and the broad flats south of Tres Hermanos in T. 27 N., R. 24 E.

LEUCOCRATIC DIKES

Hornblende Dacite.—This rock is essentially the same as the Red Mountain dacites with brown hornblende and occurs on the east side of Slagle Canyon striking southwest from the Maxwell-Chico road. Its relation to other dacites or the Slagle Canyon rocks, is not known.

Phonolite.—Phonolite porphyry forms a large dike southwest of the Chico Road and Slagle Canyon, and appears to be the parent rock of residual boulders found at Chico Breaks. The rock has a gray groundmass with light-colored, feldspar insets (1–3 mm. in diameter) and is more strongly porphyritic than other phonolites. A mineral analysis of the dike phonolite showed feldspathoid (21.3%), feldspar (70%), pyroxene (8.2%), magnetite (.6%). A few flakes of biotite, wedge-shaped crystals of sphene, and euhedral apatites were also noted. Calcite is present, probably as an alteration product. Microscopically, the groundmass consists of soda orthoclase laths, pyroxenes, occasional biotite, sphene, apatite, and magnetite. Insets of anorthoclase show hazy, cross-hatched twinning; eight-sided, acmite-diopside crystals are pleochroic and often zoned with colorless cores and bright-green borders. The mineral composition of this dike agrees with phonolites in Table 7; only the texture differs.

Tinguaite.—A dike crops out in the bottom of the creek bed where Chico road crosses Slagle Canyon. Abundant aegirine crystals color the rock green; their abundance (Pl. 4, fig. 6) through the rock distinguishes it from phonolites.

Analcime Microfoyaites.—These rocks resemble closely the analcime microfoyaite sills. Specimens essentially the same as the sill in Slagle Canyon were examined from a dike which extends southwest from Chico Road on the east side of Slagle Canyon, and from an outcrop in the Canyon south of Chico Road. The geographic proximity of these outcrops to the sill, and their essential petrographic sameness, must indicate that they bear some genetic relationship. The rocks are characterized by intersertal analcime. A little riebeckite, pleochroic from blue to green, is associated with aegirine, in addition to the minerals found in the Slagle Canyon analcime microfoyaite.

Another type of analcime microfoyaite forms the dike on Peck's Mesa and resembles the rock of the isolated knob 2½ miles north of Chico. The Peck's Mesa dike, or "fin", forms a ridge which runs near the eastern side of the mesa in a north-south direction. The specimen came from the top of the ridge and megascopically is fine-grained and medium gray, with feldspar insets (2 by .4 mm) and dark ferromagnesian crystals (.5 mm). Microscopically, it is quite different from the phonolite of the mesa top. It is holocrystalline and porphyritic with insets of analcitized feldspar, barkevikitic (?) hornblende, and acmite-diopside. The groundmass consists of soda orthoclase in bunched laths, pale-green stubby pyroxenes, a little brown hornblende, intersertal analcime, considerable magnetite, and prismatic apatite. Feldspar insets, when not almost completely analcitized, show patches of clear, untwinned feldspar (albite ?), and colorless, isotropic analcime, sometimes together with carbonate. Hornblende insets may be associated with pyroxene. Both have inclusions of magnetite and apatite.

All of these leucocratic analcime-bearing rocks, whether small intrusive knobs, sills or dikes, probably originated at rather shallow depth, where they were "quenched" or cooled suddenly, during the last phases of magmatic crystallization. This would account for the analcitization of the feldspars, and the consolidation of analcime-rich, interstitial liquid to form the wedge-shaped, intersertal patches between the earlier formed minerals.

MELANOCRATIC DIKES

Olivine Basalt.—A sugary-textured basalt, with essentially the same mineral composition as the olivine basalt flows, crops out south of Blosser Gap in Colfax County. It is a dark, aphanitic rock which microscopically shows panidiomorphic texture. Albite-twinned feldspars are in small laths, pale-tan augite abundant in the groundmass and as insets, and olivine also forms insets (.5 mm). Magnetite is scattered throughout the rock. This rock was stained and feldspathoid found absent.

Lamprophyres.—Knopf (1936, p. 1745) in describing the dikes of the Spanish Peaks region, Colorado—about 40 miles north of the New Mexico state line—discusses "The Lamprophyre Concept" and clarifies some of the nomenclature. In the Raton-Brilliant quadrangles, Mertie (Lee and Mertie, 1922, p. 11) found dikes of "basaltic rocks, such as compose the lava sheets," and "sodic vogesites . . . petrographically distinct from the basalts." The writer examined several specimens of vogesites and one specimen of monchiquite.

Vogesite is the name Rosenbusch (1887, p. 315; 1907, p. 677) gave to a syenitic lamprophyre from the Vosges Mountains, with orthoclase feldspar predominant, generally hornblende, and sometimes augite. The dikes in northeastern New Mexico are hornblende-augite vogesites and are found in the western part of the area and the vicinity of Slagle Canyon. Megascopically, these rocks are dark gray or greenish, fine-grained sometimes porphyritic. Microscopically, they are holocrystalline and porphyritic, with ferromagnesians abundant. Though commonly panidiomorphic, some dikes display an ophitic texture. Both orthoclase and plagioclase feldspars, hornblende, augite, and magnetite are present with such alteration products as carbonate, serpentine, and chlorite. The orthoclase laths form a groundmass for the more abundant hornblende and augite insets. Hornblende is in long, thin crystals (.1–1 mm), pleochroic from yellow green to brownish green, with extinction $Z \wedge c = 10°$. This small extinction angle indicates a basaltic hornblende, although the pleochroism is not the expected yellow to red. In the sodic vogesites in the Raton-Brilliant quadrangles, Mertie (Lee and Mertie, 1922, p. 12) found basaltic hornblende, altered, and showing pleochroism only in tones of yellow and brown. Groundmass augite is in pale-green, small stubby crystals; insets, sometimes showing eight-sided cross sections, are diopsidic augite ($Z \wedge c = 40°$). Hornblende insets in one specimen from a dike on the Raton-Maxwell Road, 10½ miles south of Raton, have been altered to chlorite; eight-sided sections, now carbonate or carbonate-rimmed with chlorite, indicate that these replacements are pseudomorphs after pyroxene. Other carbonate pseudomorphs have crystal outlines of olivine.

Other vogesites occur on the west side of Slagle Canyon, on the Chico Road. Specimens from the cut on the road, and from a 2-foot dike cutting the Timpas limestone, are megascopically fine-grained, dark rocks, weathering brown, with pseudohexagonal biotites (1–3 mm). Microscopically, they have biotite insets in a groundmass of orthoclase, plagioclase, hornblende, augite and accessory olivine, magnetite, and apatite. Altered hornblende is the most abundant ferromagnesian mineral and fills interstices, thus giving an intersertal or fine ophitic texture to the rock. Aggregates of chlorite, serpentine, carbonate, and fibrous iron oxides are common alteration products. Some olivine has altered to carbonate rimmed with black, opaque iron oxide.

Secondary quartz and zeolites occur, as was also noted by Mertie (Lee and Mertie, 1922, p. 12) in the Raton-Brilliant quadrangles. The biotite in these rocks makes them appear like minettes, but the mineral is not abundant enough to allow this name. Knopf (1936, p. 1768) says of some of the Spanish Peaks dikes, "augite vogesite (lamprophyres consisting wholly of potassium feldspar and augite) are the textural variants of shonkinites, and biotite-augite vogesites . . . are the lamprophyric textural equivalents of the biotite shonkinites." Biotite and olivine may both occur with augite, and then the rock is an olivine-biotite shonkinite. He found that biotite augite vogesites closely resemble minettes; that shonkinite dikes have "minette-like" margins of biotite-augite vogesite and the thinner dikes are lamprophyric from wall to wall.

The vogesites in northeastern New Mexico resemble those described as sills and dikes of hornblende-augite sodic vogesites in the Raton-Brilliant quadrangles (Lee and Mertie, 1922, p. 12), and also hornblende-augite vogesites which Cross (1914, p. 24–26) described in the Apishapa region, Colorado, north of the area being described.

Monchiquite is the name used for melanocratic dike rocks with abundant dark minerals, little or no feldspar, and an analcime base. Megascopically this is a dark-gray, porphyritic rock. Microscopically it contains pale-tan, zoned augite insets (1–2 mm) in a colorless isotropic base with augite granules and accessory magnetite, biotite, and apatite. The isotropic base is sometimes slightly birefringent and shows triangular and rounded patches. Its index of refraction is lower than balsam, and cubic cleavage lines are faintly visible in some of the minerals along the edge of the slide. Stained according to Shand's method, this material turns blue. The isotropic base is believed to be a feldspathoid, probably analcime. The rock has therefore been called a monchiquite.

SEQUENCE OF EXTRUSION

The sequence of extrustion of these lavas shows that the volcanic cycle in northeastern New Mexico began with olivine basalt extrusions in the northwestern part of the area, contiguous with flows adjoining to the west and in southeastern Colorado. After an erosion interval dacites, soda trachytes, and phonolites were erupted, as well as extensive Clayton basalts—which include olivine basalts, olivine-free basalts, olivine basalts with quartz inclusions, feldspathoid-bearing melanic rocks (basanite, nepheline basalts, and haüyne basalts). This long volcanic period, producing the most varied lavas, was followed by another period of quiescence. The volcanic cycle ended with olivine basaltic flows of less extent than the earlier ones, and explosive eruptions. Activity centered about Capulin; no less than a dozen scoriaceous and cinder cones were built up in the vicinity of this mountain. These basaltic explosions may have ended the volcanic cycle or the present quiet may be just another interval between eruptive periods.

An explanation of the basalt, trachyte, basalt sequence has been sought by Daly (1925, p. 77) in fractional crystallization.

This sequence shows a common pattern of volcanic cycles; quiet but extensive fissure flows of olivine basalt, progressing to central type-eruptions of such lavas as dacites, and ending with violent explosions. The New Mexican early basalts spread

over wide areas and were followed by the building of large dacitic cones along the crest and west flank of the Sierra Grande arch. The basalt fissure flows of the Columbia River Plateau, of greater extent, over 200,000 square miles, also were followed by central-type eruptions which built the Cascade volcanic chain of pyroxene andesites, accompanied by far-reaching explosive activity. Other similar examples could be cited.

The kind of lavas erupted in volcanic cycles generally show no regularity except that basalts may begin and end an eruptive cycle. The order in which the New Mexican lavas came to the surface is similar to that of eruptions in such areas as the Goldfield District, Nevada, (Ransome, 1909, p. 90–91) where basalts terminate a series of rhyolites, latites, andesites, and dacites and occur twice within the series. This peculiarity of basalts beginning and ending a series and the lack of order among nonbasalt lavas is not only regional; it appears on individual cones such as Mt. Taylor in western New Mexico (Fig. 1), where Hunt (1938, p. 64, 73) reports that basalt was erupted before and after a series of rhyolite, trachyte, latite, and andesite.

The sequence of these lavas over 4271 square miles in northeastern New Mexico, then, parallels several other eruptions in the western United States, as well as in other parts of the world.

THEORETICAL CONSIDERATIONS

The problem of magmatic differentiation is by no means settled, particularly in the case of alkaline rocks. Any theory of origin for the volcanic rocks of northeastern New Mexico must try to account for olivine basalt, olivine-free basalt, hornblende dacite, and alkaline rocks such as basanite, feldspathoid basalt, soda trachyte, phonolite, and analcime microfoyaite, which make this region different from near-by associated volcanic areas. Olivine basalt predominates and has been erupted at three different periods. Feldspathoid basalt and basanite in small, scattered occurrences, were probably erupted just before or during the second basalt extrusion period. Dacites, soda trachytes, and phonolites were erupted between the first and second basalt series; but, unfortunately, the relative ages of dacites, soda trachytes, and phonolites are not clear. Alkaline rocks are localized in the southwestern part of the region, where they cover only some 24 square miles. These rocks present a trachyte-phonolite-basalt association, known to occur on oceanic islands and continents the world over. Three theories have been offered to account for similar series of lavas, and may be considered for this New Mexican group of rocks.

(1) Kennedy (1933, p. 247) believes there are two parent basaltic magmas, one olivine-bearing and the other olivine-free. The inherent mineral composition of these magmas yields different residues. Olivine-free magmas differentiate into rocks of andesite, dacite, and rhyolite composition. Olivine-basalt magmas normally differentiate toward trachyandesites, trachytes, and phonolites.

(2) Bowen (1928, p. 238), Daly (1924, p. 120; 1925, p. 79; 1927, p. 74), and Shand (1933, p. 9) believe that a small amount of trachyte or phonolite may be formed from the residual portion of an olivine basalt magma.

(3) Daly (1933, p. 497) and others believe that alkaline rocks in general are the

product of a magma which has been desilicated by carbonate rocks, thus giving rise to alkaline-rich residuals.

The dual magma theory of Kennedy holds that two parent magmas underlay northeastern New Mexico, the olivine-free giving rise to dacites and the olivine magma giving rise to soda trachytes-phonolites. There are two reasons why this does not seem applicable.

(1) Olivine-bearing basalts are much larger in amount than olivine-free basalts, which would suggest that the olivine-free rocks were differentiates from the olivine basalt. In olivine-basalt regions, some basalts are richer and some poorer in olivine than the normal type. No picrite basalts, formed by settling of olivine, were found in New Mexico, as they are in Hawaii, but the olivine-free basalts resemble petrographically the olivine basalts and there is good reason to believe them to be differentiates of the latter.

(2) The minerals in the basalts are those characteristic of olivine basalts, e.g. olivine, calci-pyroxene (diopside, aegirine-diopside, titanaugite), basic plagioclase, and iron ores. Lime-poor pyroxenes (enstatite-augite and pigeonite) are not present. A basalt with the mineral composition of that in northeastern New Mexico would normally give, according to Kennedy, an alkalic residue.

Hornblende dacites are the most siliceous rocks in the area. Complete field relations between hornblende dacites and trachytes-phonolites are not known, but both occur in small amounts in the western part.

It is clearly established that small amounts of trachyte and phonolite can differentiate from olivine basalt magma, the second theory of origin. Basalt-trachyte field associations are well known—in the Auvergne District, France, Rift Valley of South Africa (Gregory, 1921, p. 194–195), oceanic islands such as Ascension (Daly, 1925, p. 75), St. Helena (Daly, 1927, p. 41, 54–56, 74–75), Mauritius (Shand, 1933, p. 9), Hawaii (Cross, 1915, p. 26–28; Stearns and Macdonald, 1942, p. 21, 323–325), Kerguelen Archipelago, Antarctica (Edwards, 1938, p. 96). In all of these occurrences the trachyte is soda-rich; in some areas phonolite occurs, and in places trachyte and phonolite grade into each other. Bowen (1928, p. 238–239) believes that a small amount of trachyte can differentiate by slow or rapid cooling provided the cooling is not too rapid to allow some fractional crystallization in the later stages. Daly (1925, p. 79) and Shand (1933, p. 9) believe that trachyte, as on Ascension Island and Mauritius, has resulted from fractional crystallization of an olivine basalt magma, and that the differentiation has depended upon the upward movement of fluids, both liquid and gaseous. However, on the oceanic islands, alkali rocks form crater fillings and spines in the midst of wide basalt effusions; and, explosive release of gases with the production of breccias and tuffs has preceded trachyte expulsion. The New Mexican phonolite lavas occur most frequently as small flows, a somewhat different occurrence from the spines on the oceanic islands. Therefore, this may not be the best explanation for the New Mexican alkali-basalt association.

Phonolites are extrusive equivalents of foyaites or nepheline syenites. The origin of foyaites through limestone assimilation is a controversal subject. Rocks at localities such as Ice River, British Columbia, Haliburton-Bancroft, Ontario, and Magnet Cove, Arkansas, are associated with limestones or have passed through

them. Rocks from Haliburton-Bancroft, Alnö, Sweden, and the Fen district, Norway, contain abundant carbonate. These examples, and many others, show quite clearly that limestone probably played a part in the origin of some deep-seated, feldspathoidal rocks. A few localities such as Cripple Creek, on the other hand, give no evidence of limestone association. To reason by analogy is dangerous, but a theory which can so admirably account for foyaites by limestone assimilation may also be considered to explain the mineralogically equivalent phonolites. Evidence, unfortunately, for the third theory—the limestone syntexis hypothesis of Daly—is even more difficult to obtain for volcanics than for intrusives, since volcanics seldom indicate as clearly as intrusives the rocks through which they have travelled. Trachyte is sometimes connected with syenite underground, as at Leeuwfontein, South Africa, but not many occurrences are recorded.

The alkaline group of New Mexico lies in a belt which extends along the approximate line of the Laramide orogeny (Fig. 3). It falls in with those other groups, both sodic and potassic, which extend from Ice River, British Columbia, to Tamaulipas, Mexico, and have been reported also from South America (Table 9). Geographically close alkaline-rock areas are the Spanish Peaks, Colorado, Cornudas Mountains on the Texas-New Mexican border, and localities in western Texas as Solitario-Terlingua (Table 9).

Although limestone rocks are associated in most of the regions, their existence in the stratigraphic column is not evidence that they have been assimilated by basalt on a large scale. If large-scale assimilation does take place, the calcareous rocks assimilated will not probably be exposed to view in that same area.

Feldspathoid basalts also are found in this general broad belt along the Rocky Mountain front (Figure 3). In New Mexico they are more closely associated in the field with olivine basalts than with soda trachytes and phonolites. The basalts associated with the alkaline rocks are free of feldspathoids. The analcime basanite, and the nepheline- and haüyne-bearing rocks belong to the Clayton eruptive period. In the crystallizing of the minerals from the lava, some nepheline was the last mineral to form, as is shown by the vesicle filling in the nepheline basalt from Robinson Mountain. All of these rocks are particularly rich in pyroxene and more melanic than the ordinary basalts. Bowen (1928, p. 269–272) believes that melanic alkaline rocks may be formed by the resorption of complex minerals such as hornblende and biotite, and that the separation of the liquids by squeezing would yield liquids strongly alkaline and at the same time rich in melanic constituents. It is possible that only a small amount of nepheline might be generated in this way, and that some other process, such as reaction with limestone, might have played a part in the development of these rare, scattered but interesting rocks. With regard to the formation of feldspathoid basalts by limestone assimilation, it is evident that the leucite-tephrites of Mount Vesuvius have resulted from assimilation of limestone in basalt, for fragments are included in the lava. Such evidence for the nepheline basalts is not so common. Tilley and Harwood (1931, p. 452, 462) have convincingly described the desilication of olivine basalt magma as it passed through a chalk formation, and the consequent formation of a small amount of nepheline-dolerite. Brouwer (1928, p. 457) has described trachyte and leucite phonolite zones surrounding inclusions of limestone in pyroxene andesite at Merapi, Java.

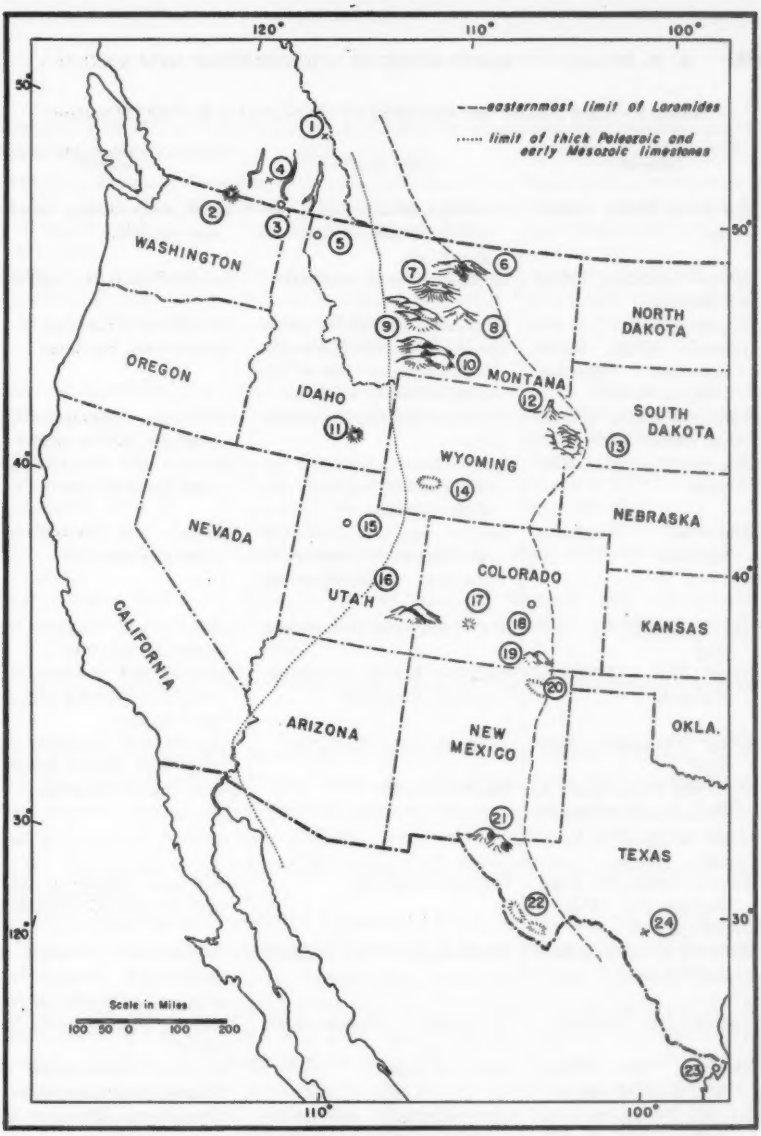

FIGURE 3.—*Map of alkaline areas along eastern front of Rocky Mountains*

1. Ice River, British Columbia.
2. Kruger Mountain, British Columbia.
3. Rossland, British Columbia.
4. Franklin Mines, British Columbia.
5. Libby, Montana.
6. Bearpaw Mountains, Montana.
7. Highwood Mountains, Montana.
8. Judith Mountains, Montana.
9. Little Belt Mountains, Montana.
10. Crazy Mountains, Montana.
11. Fort Hall Indian Reservation, Idaho.
12. Devil's Tower, Wyoming.
13. Black Hills, South Dakota and Wyoming.
14. Leucite Hills, Wyoming.
15. Stockton, Utah.
16. La Sal Mountains, Utah.
17. Iron Hill, Colorado.
18. Cripple Creek, Colorado.
19. Spanish Peaks, Colorado.
20. Northeastern New Mexico, Chico district (area described in this paper).
21. Cornudas Mountains, New Mexico-Texas.
22. Terlingua-Solitario, Texas.
23. San José, Tamaulipas, Mexico.
24. Uvalde County, Texas.

TABLE 9.—*Chief alkaline rock areas along the eastern front of the Rocky Mountains*

Location*	Alkaline eruptives*	Sedimentary rocks cut by alkaline eruptives*
1. Ice River, British Columbia	Nepheline syenite, ijolite, cancrinite syenite, urtite, tinguaite, etc.	Thick pre-Ordovician dolomites and limestone
2. Kruger Mountain, British Columbia	Nepheline syenite, malignite	Paleozoic limestone, argillite
3. Rossland, British Columbia	Missourite, monzonite, latites	Carboniferous limestone
4. Franklin Mines, British Columbia (Drysdale, 1915, p. 78–85)	Syenite, shonkinite, pyroxenite, augite syenite. Alkalic basalts, phonolitic trachytes	Carboniferous limestone
5. Libby, Montana (Larsen and Pardee, 1929, p. 97)	Nepheline syenite, pyroxenite, etc.	Belt series (Algonkian slate, quartzite, and limestone)
6. Bearpaw Mountains, Montana	Leucite basalt, nepheline basalt, leucitite, tinguaite, trachytes, syenites	Paleozoic and Mesozoic limestone and dolomite
7. Highwood Mountains, Montana	Leucite basalt, sodalite syenite, shonkinite, missourite, analcime basalt, syenites, etc.	Paleozoic and Mesozoic limestone and dolomite
8. Judith Mountains, Montana	Tinguaites, phonolites, syenite	Paleozoic and Mesozoic limestone and dolomite
9. Little Belt Mountains, Montana	Analcime basalt, shonkinite, syenite, monzonite	Paleozoic and Mesozoic limestone and dolomite, also Beltian limestone
10. Crazy Mountains, Montana	Theralite, acmite trachyte	Paleozoic and Mesozoic limestone and Beltian limestone
11. Fort Hall Indian Reservation, Idaho (Mansfield and Larsen, 1915, p. 463)	Nepheline basalt	Lower Triassic limestone
12. Devil's Tower, Wyoming, (Darton and O'Harra, 1907, p. 1–6)	Phonolite porphyry	Cretaceous sandstones, shales and intercalated limestones
13. Black Hills, South Dakota and Wyoming	Phonolite, grorudite, tinguaite	Pre-Cambrian calcareous sediments; also (locally) Paleozoic and Mesozoic limestone
14. Leucite Hills, Wyoming	Wyomingite, orendite, madupite	Paleozoic and Mesozoic limestone
15. Stockton, Utah (Gilluly, 1932, p. 48, 62–63)	Nepheline basalt	Cambrian, Mississippian and Pennsylvanian limestones
16. La Sal Mountains, Utah (Iddings, 1913, p. 425–426)	Quartz-tinguaite, noselite-tinguaite and trachyte porphyry	Paleozoic and Mesozoic limestones and shales
17. Iron Hill, Colorado (Cross and Larsen, 1935, p. 17–43; Larsen, 1942, p. 2–4)	Melilite rocks as uncompahgrite; pyroxenite, ijolite, soda syenite, nepheline syenite, and theralite	Intrudes pre-Cambrian granite. Associated with crystalline limestone at contact
18. Cripple Creek, Colorado	Nepheline syenite, phonolite, syenite, trachydolerite	Intruded into Pre-Cambrian granite

TABLE 9—*Continued*

Location*	Alkaline eruptives*	Sedimentary rocks cut by alkaline eruptives*
19. Spanish Peaks, Colorado (Knopf, A., 1936, p. 1727–1784)	Shonkinite, analcime syenogabbro; lamprophyre dikes	Cretaceous sandstone, shale, and limestone lenses
20. Northeastern New Mexico, particularly the Chico district (Collins, 1949)	Phonolites, soda trachytes, analcime microfoyaites, basanites and feldspathoid basalts (nepheline basalt and haüyne basalt)	Cretaceous sandstones, limy shales, and limestone lenses
21. Cornudas Mountains, New Mexico-Texas (Clabaugh, 1941; Timm, 1941; Zapp, 1941)	Augite syenite, analcime nepheline syenite, tinguaites, etc.	Permian limestones and redbeds; Cretaceous sandstones, conglomerates and limestones
22. Terlingua-Solitario, Texas (Lonsdale, 1940, p. 1539–1626)	Trachytes and analcime rocks as analcime nepheline syenite, etc.	Paleozoic and Cretaceous limestone and shale
23. San José, Tamaulipas, Mexico	Nepheline syenite, camptonite, syenite, tinguaite	Thick Cretaceous limestone
24. Uvalde County, Texas	Nepheline basalt and basanite, melilite basalt, phonolite, limburgite	Mesozoic (and older?) limestones and marls

* Except when reference is given, the locality and data for eruptive rocks and associated sediments are taken from Daly (1914, p. 512–514, 516).

The following explanation is offered to account for the diverse rocks in northeastern New Mexico. It is evident from its wide distribution that olivine basalt was the parent magma. As the olivine magma proceeded to crystallize and differentiate, olivine-free basalts were formed by crystal settling or sinking of olivine crystals. The alkalic types may have resulted from reaction with limestone at depth, as Daly supposes.

This explanation accords with the sequence of the rocks, for the nonbasalts came later than the early olivine basalts and probably were differentiates of the early basalt magma. The feldspathoid basalts also came later than the early basalts. Erosion periods between eruptions allowed for fractional crystallization and formation of different magma types, and, after these types were emitted and had drained the magma chamber, it was again filled with olivine basalt from a lower stratum which gave rise to the later, intermediate and recent olivine-basalt effusions which closed the volcanic cycle.

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Smith College, Northampton, Mass.

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FIGURE 1. MOUNT CAPULIN SEEN FROM NORTH ON HIGHWAY 64
Flow of Capulin basalt down Dry Cimarron Valley shows to right.

FIGURE 2. BASALT BLOCKS AND BOMBS INSIDE CRATER OF MOUNT CAPULIN

FIGURE 1

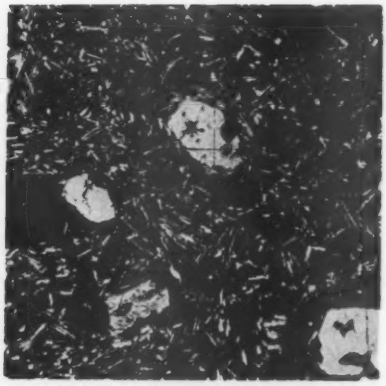
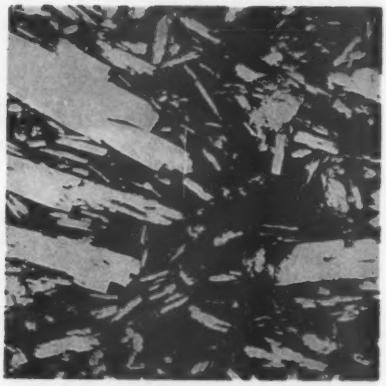


FIGURE 2

FIGURE 3



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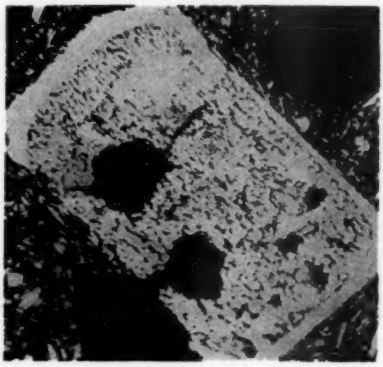


FIGURE 5

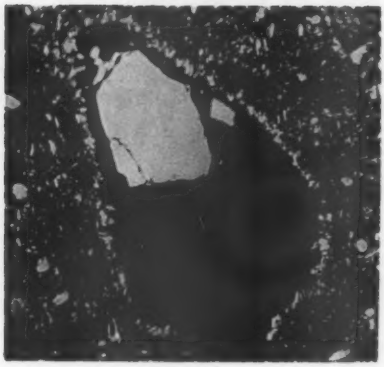


FIGURE 6

PHOTOMICROGRAPHS OF OLIVINE BASALTS

EXPLANATION OF PLATES

PLATE 2.—PHOTOMICROGRAPHS OF OLIVINE BASALTS

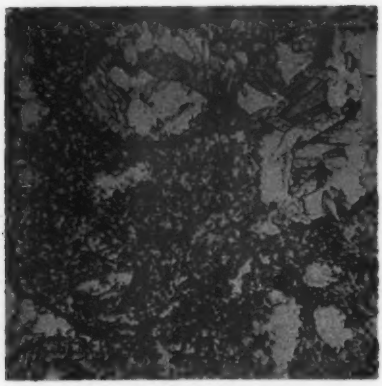
Figure

1. Olivine basalt from Clayton flows with iddingsite bordering the larger olivine crystals and completely replacing the smaller grains. Large mesa from Sierra Grande to Clayton. Crossed nicols. × 40
2. Typical Raton olivine basalt with olivine insets. West edge of Johnson Mesa, Colfax County. Crossed nicols. × 40.
3. Coarse-textured, Raton olivine basalt with feldspar laths dominant and interlacing, interstitial augite, and olivine insets. Mesa north of Valley Post Office. Crossed nicols. × 47
4. Capulin olivine basalt with feldspars in glassy matrix. Round grain of olivine shows in lower right of picture. Flow from Mount Capulin down Dry Cimarron Valley. Plane light. × 47
5. Feldspar crystal typical of Capulin basalts showing clear, outer zone and interior portion with groundmass inclusions. West base of Mt. Capulin. Crossed nicols. × 40
6. Quartz inclusion and augite reaction rim in nepheline basalt from Clayton series of basaltic flows. Second outlier west of Yankee Volcano, Colfax County. Crossed nicols. × 40

PLATE 3.—PHOTOMICROGRAPHS OF FELDSPATHOID BASALTS, DACITES, AND ANDESITE

Figure

1. Nepheline basalt from Clayton basalts showing vesicles filled with euhedral nepheline, yellow-brown glass (colorless in picture) and acmite-diopside crystals which can be identified by cleavage. Magnetite grains border vesicles. Robinsons Peak, 7 miles southwest of Folsom. Plane light. × 40.
2. Haüyne basalt showing haüyne crystals (lower middle and upper right) with dusty interiors and clear rims. Pyroxene cluster in upper left corner. Low hill at north end of Hunter Mesa. Plane light. × 40.
3. Hornblende dacite showing porphyritic texture and red-brown hornblende crystals with narrow borders of magnetite granules. Groundmass composed of feldspar, tan glass, and magnetite. East side of Towndrow Peak, Johnson Mesa. Plane light. × 47.
4. Hornblende dacite showing large brown hornblende inset partially altered to magnetite, and smaller crystals completely changed to magnetite. Top of Towndrow Peak, Johnson Mesa, Colfax County. Plane light. × 47.
5. Hornblende dacite with early formed oligoclase-andesine crystal with groundmass inclusions. Northeast slope of Green Mountain. Plane light. × 47.
6. Hornblende andesite with hornblende (lower) and pyroxene (upper left corner) crystals in fine-grained groundmass. Near top of Turkey Mountain on southwest flank, Colfax County. Plane light. × 45.



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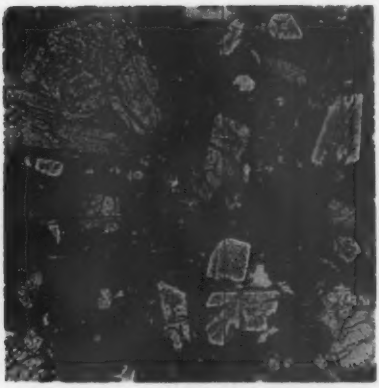

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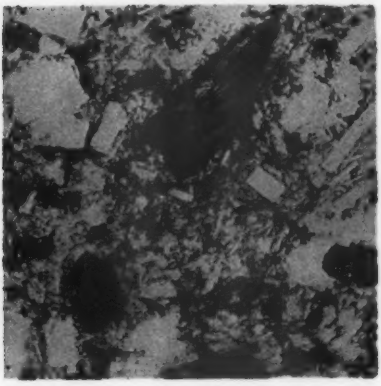

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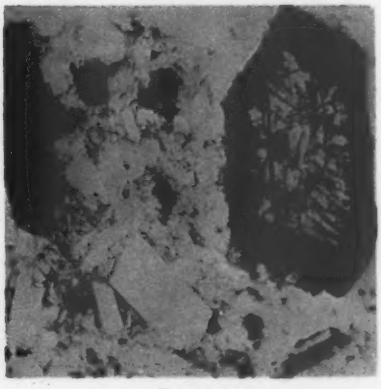

FIGURE 4

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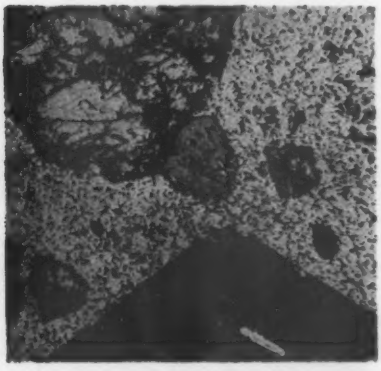

FIGURE 6

PHOTOMICROGRAPHS OF FELDSPATHOID BASALTS, DACITES, AND ANDESITE

FIGURE 1

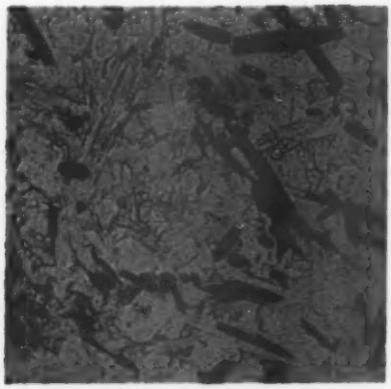

FIGURE 2

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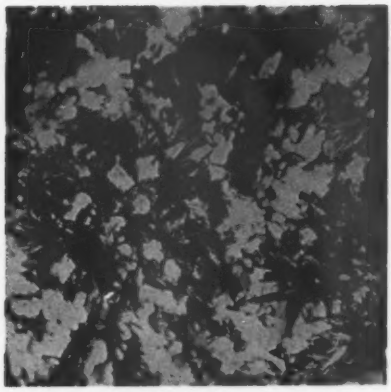

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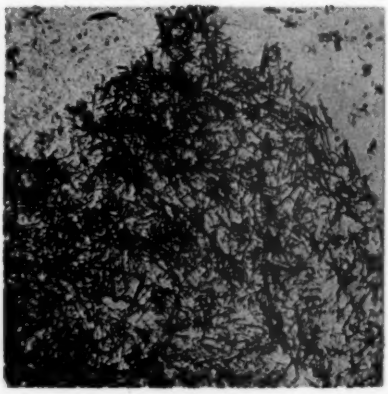

FIGURE 5

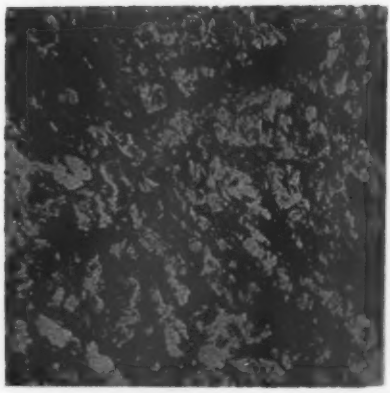

FIGURE 6

PHOTOMICROGRAPHS OF PHONOLITES AND TINGUAITE

PLATE 4—PHOTOMICROGRAPHS OF PHONOLITES AND TINGUAITE

Figure

1. Analcime ocelli with tangential aegirine crystals (upper right corner) in porphyritic phonolite. Acmite-diopside crystal shows at bottom. Two miles southeast of Timber Buttes. Plane light. × 40.
2. Phonolite with aegirine crystals distributed in flow bands. Light minerals are soda orthoclase and euhedral nepheline. Top of Temples Peak. Plane light. × 47.
3. Euhedral nepheline inclusions in aegirine clusters in phonolite. South side of Laughlin Peak, Colfax County. Plane light. × 40.
4. Same rock under crossed nicols. Interstitial nepheline (white) shows in left and right central parts of picture. × 40.
5. Phonolite with tinguaitic habit. Needle-like aegirines are scattered abundantly throughout the slide. Portions of soda orthoclase insets show in upper left and right corners. South Kiowa Mesa. Plane light. × 45.
6. Tinguaite dike showing euhedral nepheline, soda orthoclase and abundant aegirines, interstitial between the light minerals and included in nephelines. Dike where Chico road crosses Slagle Canyon, Colfax County. Crossed nicols. × 45.

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